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PHYTOPLANKTON PRODUCTIVITY IN LAKE WABAMUN, ALBERTA, AND THE EFFECT OF THERMAL EFFLUENT

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled

Phytoplankton productivity in Lake Wabamun,
Alberta, and the effect of thermal effluent.

submitted by Leigh R. Noton

in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

Two thermal electric generating plants discharge heated effluent water to Lake Wabamun, a moderately eutrophic central Alberta lake (mean depth, 5.4 m; area, 82.5 km^2). This study investigated phytoplankton productivity and associated parameters in heated and unheated areas of the lake.

Phytoplankton productivity (in situ : oxygen method in 1970, C^{14} method in 1971-72), cell numbers, chlorophyll a, plus chemical and physical parameters, were sampled from spring, 1970 to August, 1972. Heated and unheated areas were compared by near simultaneous sampling.

Summer surface water temperatures were about 20 °C (max 23.5 °C), no thermocline established, and ice cover (max 1 m ice and snow) was from early November to May inclusive. Discharge temperatures were about 8 and 15 C° above ambient, in summer and winter respectively. Effluent areas did not freeze.

Turbidity (with Secchi disc) was consistently higher in effluents. Light penetrated the water column all year in the effluents, but was strongly reduced by ice and snow cover in the main lake.

Wabamun is a hardwater, bicarbonate lake. Thermal discharges did not affect concentrations of dissolved solids.

Phytoplankton cell numbers showed spring and late summer maxima (max 30,000 cells/ml), the latter dominated by blue-greens. Winter lows were about 1500 cells/ml. Counts are presented for blue-green algae, green algae, diatoms, flagellates, and ultraplankton. Species composition was not affected by thermal discharges and cell numbers were only occasionally affected.

Phytoplankton mean chlorophyll a concentrations were 1.0 to 16.4 mg/m³ in March, 1972, and July-August, 1971, respectively. An individual high was 19.1 mg/m³. Chlorophyll differences between heated and unheated areas followed cell number differences.

Main lake phytoplankton productivity generally corresponded positively with cell numbers, chlorophyll a, and turbidity. All were lowest under snow-covered ice.

Summer midday productivity (max 115.8 mgC/m³/hr) averaged 35% of daytime production (max 3,045 mgC/m²/day). The latter averaged 1500 mgC/m²/day in July-August, 1971, in the main lake. Productivity was greater in effluents, the increases being positively correlated with temperature increases. Percentage increases in both parameters were greatest near the surface and in winter.

The Q_{10} for all production increases was 2.6. Assimilation ratios (max 8.6 in the main lake) were similarly enhanced, indicating photosynthesis was stimulated, by direct temperature effects and/or increased nutrient availability.

Phytoplankton daytime net primary production in the

main lake was 170 gC/m²/yr. Thermal discharges increased this by 2%, largely because of winter ice-free conditions. Thermal effects on overall plankton metabolism are unknown.

This increase in phytoplankton productivity is not considered harmful.

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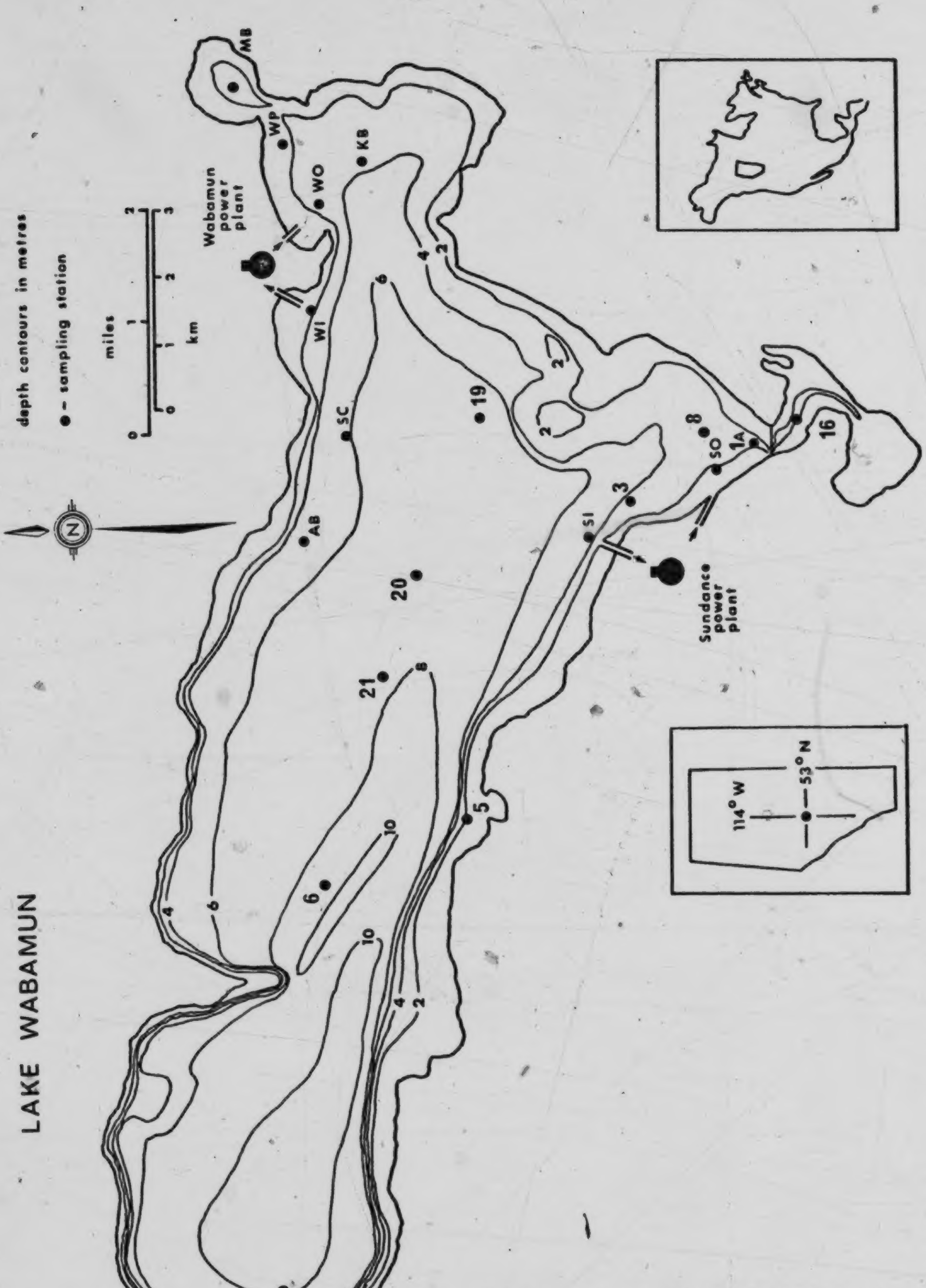
INTRODUCTION

Lake Wabamun is a relatively large lake in central Alberta, situated 40 miles (64 km) west of Edmonton. It is moderately eutrophic, non-stratifying, and has a six-month ice-free season lasting from late April to early November. Morphometric data for the lake are presented in Table 1, and a map of the lake is presented in Figure 1.

Human use of the lake in the form of recreational pursuits (private cottages, boating, swimming, camping, fishing, water skiing, hunting, nature study) and commercial use (municipal water supply and sewage disposal, power plant cooling water supply, commercial fishing) is relatively intensive and has resulted in conflicts of interest between recreational and commercial users. The main issue in this conflict is the use by Calgary Power Ltd. of lake water for cooling steam condensers in their two electric generating stations (Figure 1), and the subsequent discharge of this water back to the lake at temperatures some 8 to 15 C° above ambient. This warm water discharge, or thermal pollution, keeps a variable area of the lake surrounding the discharge canals at warmer temperatures than the rest of the lake and prevents it from freezing in winter. After leaving the discharge canals, the warmed water spreads out in the receiving waters, forming a warm layer of variable thickness floating on the cooler denser water below and often separated from the cooler bottom water by a sharp


LAKE WABAMUN
depth contours in metres
● - sampling station
miles
0
1
2
km
0
1
2
3
N
Wabamun power plant
Sundance power plant
MB
Wp
WO
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WI
SC
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SI
SO
1A
3
5
6
8
16
19
20
21
2
4
6
8
10
114° W
53° N

Figure 1. Outline of Lake Wabamun, with depth contours, power plants, sampling stations, and geographical location.

temperature gradient, in effect, a thermocline. As the warm water spreads out from the discharge canal it slowly cools to ambient temperatures such that within this 'thermal plume', both surface temperature and thickness of the warm layer decrease with increasing distance from the discharge canal. The size, shape, and depth of the thermal plume are noticeably affected by local weather conditions, especially wind, and the size and shape of the ice-free area in winter are affected by air temperature and prevailing winds.

TABLE 1

Morphometry - Lake Wabamun[1]
(symbols from Hutchinson, 1957)

Elevation	722.7	m
Area (A)	82.5	Km^2
Volume (V)	ca. 0.455	Km^3
Length (l)	19.2	Km
Maximum breadth	6.6	Km
Mean breadth (b)	4.3	Km
Maximum depth (z_m)	11.6	m
Mean depth ($\bar{z}$)	5.4	m
Shoreline length (L)	57.3	Km
Shoreline development (D_L)	1.83	
Area of surface drainage	372.4	Km^2

[1] Nursall and Gallup, 1971

Public interest in the effects of thermal effluents on Lake Wabamun has arisen largely as a result of excessive growths of submerged aquatic plants which interfere with recreational use of the lake and are alleged to be a result of the thermal discharges. This interest was centered on the area around the older generating station (capacity approximately 600 megawatts) at the town of Wabamun, but fears were also expressed about the effects of heated effluent from the newer Sundance plant, which commenced operations in the fall of 1970 (at 300 Mw) and was expected to expand its capacity (to an eventual 1200 Mw) over a number of years. Partly as a result of these concerns, a number of investigations have been carried out on the lake.

Apparently the first reports on Lake Wabamun were those of Miller (1946; 1947; 1952) who studied various aspects of the whitefish fishery in the lake. Carefoot (1959) made brief mention of the algal characteristics of the lake. In a report commissioned by Calgary Power Ltd., Stanley and Dobson (1961) reported on the physical characteristics and aquatic macrophytes of Kapasiwin Bay. Anderson (1967) studied recreational aspects of the lake, Wheelock (1969) reported on phytoplankton ecology in the lake and effects of thermal pollution, Lane (1970) investigated the sports fishery, Horkan (1971) studied the general environmental impact of the heated effluent, specifically its effects on rotifers, and Carlson (1971) produced a report on the bedrock topography of the Wabamun Lake region. Physical parameters of the lake, including a discussion of water balance, are found in Nursall, Nuttall, and Fritz (1972), and Fritz and Krouse (1973). A report concerning a micrometeorological study of the lake is given by Hage, Honsaker, and Nuttall (1973). Temperature and dissolved oxygen characteristics of the heated areas are described in Gallup and Hickman (1973), Gallup and Hickman (1974), and

Klarer, Hickman, and Gallup (1973). General effects of the thermal effluent on the biota of the lake are given in Nursall and Gallup (1971), and phytoplankton productivity studies are reported on by Noton (1973). A study by Klarer (1973) formed the basis for several reports (Hickman and Klarer, 1974a; 1974b; Klarer and Hickman, 1974) on epiphytic algae and their responses to thermal discharges. Hickman (1974) investigated thermal effects on the algae of the epipelon and epipsammon. The submerged macrophytes were the subject of studies reported in Allen and Gorham (1973), and Allen (1973), and ecological effects of macrophyte control practices were described by Gallup, Rasmussen, and Hickman (1973), and Griffing, Saponja, and Krochak (1974). Ash (1974) described thermal effects on whitefish while Sankurathri (1974) investigated the ecology and parasites of aquatic snails in thermally affected areas. At present, studies are continuing on submerged macrophytes, the influence of weather and thermal effluents on lake currents, and the distribution of benthic macroinvertebrates in the heated areas.

The present study concerning phytoplankton productivity was undertaken because this aspect of lake biology is basic to an understanding of a freshwater ecosystem but had not been previously investigated in Lake Wabamun. Furthermore, aside from a few cursory observations by Pinsent (1967), Lin (1968), and perhaps others, there have been only three major investigations of phytoplankton productivity in Alberta;

those of Fabris (1966) on four small mountain lakes in Banff National Park, Donald (1971) on three temporary ponds close to Calgary, and Anderson (1968, 1974), on several mountain lakes and ponds. Thus it was felt that a study of phytoplankton productivity in Lake Wabamun would at least partially fill a gap in the knowledge of central Alberta lakes.

Prior to the start of this study, to my knowledge, only two papers had been published dealing with the effects of thermal pollution on phytoplankton productivity. Warinner and Brehmer (1966) had investigated this problem in the York River estuary, Virginia, and Morgan and Stross (1969) studied the subject in the Patuxent River estuary, Maryland. Both studies used productivity determinations carried out under laboratory conditions. Therefore it was felt that a study of thermal effects on phytoplankton productivity in Lake Wabamun, using in situ productivity determinations, in conjunction with the general study of productivity, would be very useful not only in describing thermal effects in Lake Wabamun, but as a general contribution to this aspect of thermal pollution studies. There were no previous such investigations at these latitudes, or on lakes, or using in situ productivity determinations. Subsequently, several publications have appeared concerning phytoplankton productivity and thermal pollution (Hamilton et al., 1970; Hirayama and Hirano, 1970; Wapora, 1970; Koss, 1971; Williams et al., 1971; Brook and Baker, 1972; Gurtz and

Weiss, 1972) and three (Patalas, 1970; Pidgaiko _et al_., 1972; Tilly, 1973) which involved _in situ_ determinations in a freshwater lentic ecosystem.

There were thus two main objectives in this study of Lake Wabamun. The first was to investigate annual phytoplankton productivity and attendant parameters, including phytoplankton standing crop, phytoplankton chlorophyll _a_, and chemical and physical factors. The second was to investigate the effects of warm water effluents on the above factors. This report will not attempt to present a detailed description of the lake or the thermal effluent characteristics, however, as this has been done in previous publications. For such descriptions, the reader is referred to Horkan (1971), Nursall and Gallup (1971), Gallup and Hickman (1973), Klarer, Hickman, and Gallup (1973), and Allen (1973).

MATERIALS AND METHODS

A. General

The investigations consisted largely of field sampling, observation, and experimentation. Laboratory work was confined to analyzing samples and data collected in the field. Figure 1 shows the location of all stations sampled in this study. Sampling depths varied with time and station, but in general, the depths of 0 m, 0.5 m, 1.0 m, and 2.0 m, were sampled consistently in the effluent areas and at stations to which they were to be compared. Stations in the main lake were frequently sampled at depths that would give adequate representation of the total water column.

Sampling commenced on May 22, 1970, and continued to August 2, 1972. During the summer of 1970, investigations were largely confined to the main lake and to the Sundance area, in an effort to obtain data in the latter region while it was still unaffected by a warm water effluent. Sampling stations (SO, SI, 3 to 8, and 19, Figure 1) were chosen to include areas of the lake likely to be affected by warm effluents when the Sundance power plant started operations, similar near shore areas that would not likely be affected, and areas in the main body of the lake. The Wabamum heated area was sampled occasionally as well. Productivity incubations were carried out twice weekly at first, then reduced to once a week, and stopped for the winter on November 2, 1970. During 1970, the oxygen method of measuring productivity (discussed later) was used.

Because of the relative insensitivity of the oxygen method and the long incubation periods required, the C^{14} method of measuring productivity was investigated during the winter of 1970-71, and used from June 28, 1971 to the end of the study. Chlorophyll a determinations were started in May, 1971, and used to the end of the study also. From the summer of 1971 and later, both the Wabamun and Sundance warm water effluents were sampled and compared with an open lake station, station 19, by using 'simultaneous' incubations at the two stations to be compared. Main lake productivities were still being monitored as well. Several special investigations were carried out, including diurnal studies, detailed vertical sampling, and comparisons between control stations. During the winter of 1971-72, logistical problems prevented sampling the Sundance area and use of simultaneous incubations to compare the Wabamun heated area with an ice-covered site. However, two sites (stations WO and KB, Figure 1) were simultaneously sampled in the Wabamun ice free area at that time. The main lake stations sampled during winter were SC and AB (Figure 1). During summer, 1972, unheated littoral stations (WI, WP, 1-A, 3, SI, Figure 1) similar to the warm water sites were chosen and utilized as additional controls. All sampling was completed on August 2, 1972.

When fully sampling a station in the lake, the general procedures used consisted of the following, in the order in which they were done:

1. Water temperatures, weather observations, snow and ice depths (when present) were recorded;
2. Water samples from different depths were collected with either a plastic Van Dorn or a plastic Kemmerer water sampler, to fill productivity incubation bottles and to supply phytoplankton samples, phytoplankton chlorophyll a samples, and water chemistry samples;
3. Productivity incubation bottles were prepared and set out to incubate *in situ* ;
4. A Secchi disc visibility measurement was taken;
5. Light measurements were taken when desired;
6. During the incubation period, operations such as the set up of productivity filtration apparatus, total carbon dioxide determinations, and Winkler oxygen titrations, were carried out;
7. Close to the end of the incubation period, water temperatures were again recorded to give a more accurate estimation of mean incubation temperatures;
8. Incubation bottles were picked up, and the contents either filtered (C^{14} method) or chemically fixed and titrated (dissolved oxygen method).

Field operations were carried out from a 16-foot boat with outboard motor during the summer. For winter operations, a smaller boat and motor were used in the ice-free area at Wabamun. A four-wheel-drive vehicle equipped with tire chains was utilized in winter to transport onto the ice the equipment needed for productivity investigations. A nine-foot-square tent (Plate 1) with a hole in the floor and a heater, facilitated sampling through the ice by keeping samples, equipment, and fingers from freezing. A small house trailer parked on Calgary Power Ltd. property from the spring of 1971 on, provided facilities in which to store field equipment and carry out total carbon dioxide determinations and sample filtration.

Plate 1. Winter sampling.

Plate 2. Incubation bottle-float assembly.

B. Specific Procedures

1. Phytoplankton Primary Productivity Measurement

(a) Oxygen Evolution Method

This method of quantifying phytoplankton productivities uses the change in lake water oxygen concentrations within light and opaque glass sample bottles incubated _in situ_, as an index of community metabolism (see Vollenweider, 1969). This method was used during the summer of 1970.

Water samples were added to four 300-ml ground-glass-stoppered bottles from a Van Dorn water sampler, the water being allowed to overflow during this process to remove all air bubbles. Two light bottles, one dark bottle, and one initial bottle (for determination of the initial oxygen concentration), were filled from each depth or location sampled. Zooplankton was not filtered out of the samples first. Dark bottles were wrapped in black plastic tape, then aluminum foil to exclude light and prevent excessive heating from sunlight. Light and dark bottles were filled and stored under dim light conditions to reduce adverse effects of strong light on the algal cells. When all the required bottles for a station were filled, the light bottles and dark bottles were suspended at the depths of collection, on separate lines attached to opposite ends of a two-meter iron rod, which was tied across an inner tube float (Plate 2). The float was positioned with two anchors such that the light bottles were on the south side of the assembly to prevent their being shaded by the float. After setting out the bottles, the 'initial' bottles were fixed and titrated according to the azide modification of the Winkler dissolved oxygen technique. Incubation periods were about nine hours long, centered on noon. At the end of the incubation period, the bottles were retrieved, fixed with alkali-iodide-azide and manganese sulfate, and titrated. Small plastic powder pillows (Hach Chemical Co.) containing the necessary Winkler reagents were used in this work because of their convenience.

Productivity rates were calculated from the oxygen changes and expressed as mgC/m^3/hr of incubation, assuming a photosynthetic quotient of 1.2 (Ryther,1956).

(b) Carbon^{14} Method

The C^{14} method for measuring phytoplankton photosynthesis, described in Vollenweider (1969), involves adding $C^{14}O_2$ to water samples and measuring C^{14} uptake by the plankton after a suitable incubation period. If the amount of $C^{12}O_2$ available in the water is known then the productivity (C^{12} uptake) can be calculated from the general formula:

$$\frac{C^{14} \text{ uptake} \times C^{12} \text{ available}}{C^{14} \text{ addition}}$$

This method, using *in situ* incubations and liquid scintillation counting of labelled algae (Schindler, 1966), was used from June 28, 1971 to the end of the sampling period.

Radioactive carbon was obtained as a $NaHC^{14}O_3$ solution from Amersham-Searle Ltd. This solution was diluted to an appropriate concentration (see below) with 'distilled' water having a pH of about 9.5 (adjusted with NaOH), and the solution was transferred to 10 ml glass ampoules. The ampoules were sealed with a torch and then sterilized. This was the solution to be added directly to the productivity incubation bottles. The radioactivity of this solution was in the order of 4-10 microcuries/ml, depending on the season: more activity was required when productivities were low. Absolute activity of a batch of these ampoules was determined by appropriately diluting the contents of a few ampoules, adding a known small volume of this diluted solution directly to a scintillation counting vial containing liquid scintillator, and counting immediately in the scintillation counter. It should be noted that after these scintillation vials had stood for a few days, they lost a portion of their radioactivity, presumably because of escape of gaseous $C^{14}O_2$. This inadequacy in the technique is assumed to be overcome by counting the vials as soon as possible. DeCosta and Volkmar (1974) have considered this problem further. Scintillation counting was done on a Nuclear Chicago Mark 1 liquid scintillation counter (Nuclear Chicago Corp.). The scintillation solution used was Bray's solution (Bray, 1960). In order to determine counting efficiencies of the counter assembly, a channels ratio quench correction curve (Wang and Willis, 1965) was prepared using a C^{14}-hexadecane standard (Amersham-Searle Ltd.). The standard was added to a series of vials containing a wide range in concentration of the quenching agent. Normal Lake Wabamun plankton, filtered from lake water onto HA Millipore filters, acted as the quencher. Counting efficiencies of around 80% were obtained with the counter in this study.

Field procedures were similar to those of the oxygen method in that two light bottles and one dark bottle were used for each depth. No initial bottle was necessary. The dark bottles were used to estimate non-photosynthetic uptake of C^{14}. The incubation bottles were smaller, however, being 128 ml. Zooplankton was not filtered from the water prior to filling the incubation bottles. In field procedures, after all the bottles were filled with the sample water, each was inoculated with 0.5 ml of the radioactive working solution, by means of a 1 ml syringe fitted with a 6 cm needle. The long needle allowed the C^{14} solution to be added well below the neck of the incubation bottle to avoid C^{14} loss when stoppering the bottle. The bottles were then shaken to distribute the C^{14} within them, and suspended in situ for a four hour incubation period, normally centered on noon.

When the productivities of two stations were to be compared, the whole sampling procedure could be completed within 40 minutes so that incubations at the two stations were started within 40 minutes of each other.

This was done during 1971. In 1972, operations were further modified such that the 'simultaneous' incubations could be started within 10 minutes of each other. At the end of the incubation period, the bottles were picked up, placed in a dark box, and taken to the trailer. There the samples were filtered immediately using graduated glass filtration tubes and filter flasks attached by a manifold to an electric vacuum pump (Plate 3). Membrane filters of pore size 0.45 μ (HA filters-Millipore Ltd.) were used in these tubes. At the end of filtration, the filters and their contained algae were rinsed in place with about 10 ml of filtered non-radioactive lake water, then placed immediately, while still wet, into the scintillation vials. This was done to prevent loss of any volatile labelled compounds (Wallen and Geen, 1968; Ward and Nakanishi, 1971). The amount of water filtered from the incubation bottles varied from 30 to 60 ml, depending on how much could be conveniently passed through the filter without excessive clogging.

In the winter of 1971-72, several incubations were carried out under the ice. Since snow and ice cover drastically reduces light penetration into a lake, and therefore photosynthesis, it was desirable to incubate the bottles under snow and ice that was not disturbed. This was accomplished by attaching the normal iron suspension rod, slightly inflated inner tube, and incubation bottles to an ice jigger after the usual sample collection and preparation, and jigging this assembly under the ice as far away from the sampling hole as was convenient, so that it was situated under an area of undisturbed ice and snow.

Plate 3.
Filtration apparatus.

Plate 4. Ice jigger
with photometer.
Wabamun power plant
in background.

The total amount of carbon dioxide available in the water was determined for each productivity incubation depth and location using the titrimetric method outlined in Standard Methods (Amer. Public Health Assoc., 1965). The total carbon dioxide value obtained was multiplied by 0.27 (the proportion of carbon in carbon dioxide) to give total carbon available, and expressed as mgC/m^3.

Arthur and Rigler (1967) pointed out the possibility of algae being crushed during filtration in the C^{14} productivity method and thus losing some of their radioactivity. They suggested that by filtering different volumes of labelled algae (i.e. lake water from incubation bottles) and plotting the results as volume filtered versus unit radioactivity, a curve could be obtained relating the two and a correction factor for this effect deduced by extrapolating the curve to zero volume filtered. Three such experiments were done in this study to determine this correction factor, the mean value of which was 1.65. Initially, this correction factor was used in calculating results.

Since the start of this study, however, two papers have appeared (Nalewajko and Lean, 1972; McMahon, 1973) which question the validity of the use of the correction factor. On the basis of the evidence presented by these authors, it was decided not to employ the correction factor, and all productivity results reported here have been revised downward appropriately.

An isotope correction factor of 1.06 was also used.

Results (productivity) were calculated as mgC/m³/hr using the formula:

$$\frac{C^{14}\text{ uptake x }C^{12}\text{ available x 128 x 1.06}}{C^{14}\text{ added x E x F x T}}$$

where

C^{14} uptake is in cpm and is the mean light bottle value minus the dark bottle value,
128 is the volume in ml of the incubation bottle,
1.06 is the isotope correction factor,
C^{14} added is in dpm (disintegrations/min),
E is the scintillation counter efficiency,
F is the volume filtered,
T is the incubation time in hours.

2. Phytoplankton chlorophyll a determinations

Chlorophyll a content of phytoplankton was determined using the spectrophotometric method and equations of Moss (1967a; 1967b). Water samples were filtered through Whatman GFC glass fiber filters (W.&R. Balston Ltd.) and the filters were placed in buffered 90% acetone, shaken well, and stored in the dark at sub-freezing temperatures for at least 24 hours to allow pigment extraction to occur. The acetone solution was then read in a spectrophotometer at wavelengths of 750 mu, 665 mu, 430 mu, and 410 mu. After this initial reading, the acetone plus pigment solution was acidified to convert all chlorophyll to pheopigments, reneutralized, and reread at 430 mu and 410 mu. The ratio of optical densities at 430 mu and 410 mu is an indicator of the proportion of pheopigments to the total chlorophyll a and pheophytin pigments. This ratio was then applied to the chlorophyll a value calculated from the 665 mu optical density to correct for the presence of the chlorophyll degradation products. Results were expressed as mg chlorophyll a /m³ of lake water.

This method was used from May 20, 1971, to the end of the study. Water samples for chlorophyll a analysis were collected at every depth and location where a productivity incubation was carried out. After collection, water samples were stored in the dark at temperatures no higher than the original temperature of the sample, and transported to the lab where they were filtered no later than 12 hours after collection.

3. Phytoplankton Identification and Enumeration

Unconcentrated phytoplankton samples (i.e. lake water) were collected throughout the study from each depth and location of productivity incubation as well as from many other depths and locations. Samples were preserved with 'Lugol's' solution (Vollenweider, 1969: p. 7). Only selected samples from June 28, 1971, and on, were identified and enumerated.

Permanent, quantitative microscope slides were made from the selected samples for identification and enumeration of phytoplankton. Permanent slides were desirable in this situation since they gave a durable, quantitative record that could be repeatably referred to, examined under ordinary compound microscopes, and used for algal identification since the mounting medium employed gave little distortion of specimens. The slides were prepared using a modification of the method of Coulon and Alexander (1972) in which the desired volume of sample was placed in a settling tube slide assembly (Figure 2) to allow the plankters to sediment. The supernatant was removed after sedimentation was complete, and two drops of the mounting medium (Aquamount-Edward Gurr Ltd., a water-soluble, non-shrinking mounting medium) were added to the remaining water and sediment and the slide was allowed to dry. When drying was finished, the middle slide was removed, and a coverslip, with a drop of Aquamount, added to the preparation. Unfortunately, a random distribution of plankters on the slide was not obtainable because of the turbulence induced in the water and sediment upon addition of the mounting medium, so that when enumerating the cells, the position of the fields to be counted had to be chosen randomly. This was done using a system of randomized microsope stage co-ordinates. Examination of the slides was usually done at 400x with a Vickers compound microscope. Ten to twenty fields were counted per slide.

Knowing the microscope field area, the number of fields counted, the volume of sample sedimented, and the sedimentation area, (i.e. cross sectional area of the sedimentation tubes) allowed calculation of the results as algal cells per ml of original sample.

Generally, algae were identified only to the generic

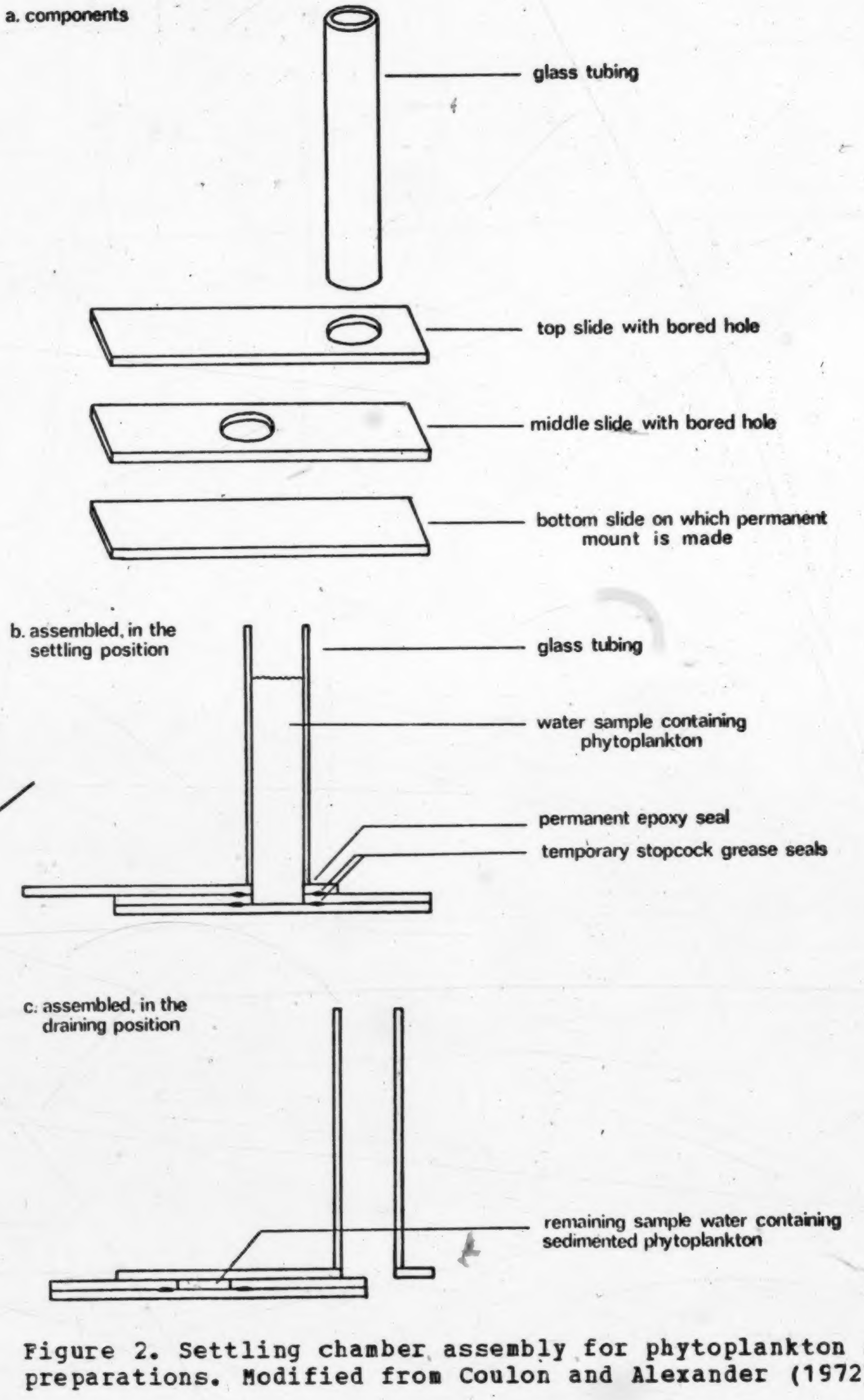

a. components
glass tubing
top slide with bored hole
middle slide with bored hole
bottom slide on which permanent mount is made
b. assembled, in the settling position
glass tubing
water sample containing phytoplankton
permanent epoxy seal
temporary stopcock grease seals
c. assembled, in the draining position
remaining sample water containing sedimented phytoplankton

Figure 2. Settling chamber assembly for phytoplankton slide preparations. Modified from Coulon and Alexander (1972).

level. For purposes of data presentation, the phytoplankton were placed into the following five major groups: Cyanophyta (blue-green algae), Chlorophyta (green algae), Bacillariophyta (diatoms), Flagellates (Chrysophyceae, Cryptophyceae, Dinophyceae), and the Ultraplankton, the small, unidentifiable plankters up to 5 μ in one dimension as described by Naumann, in Hutchinson (1967, p. 235-236). The keys in Smith (1950) and Prescott (1962) were used to identify algae.

4. Water chemical analysis

Weekly during summer and monthly during winter, samples were collected for chemical analysis of the lake water, and kept cool and in the dark until arrival at the lab, where they were frozen. During 1970, these samples were analyzed by the lab at Environmental Health, Government of Alberta, and during 1971-72 by Mrs. G. Hutchinson in the Department of Zoology Water Analysis Lab. Samples were filtered, then analyzed for pH, specific conductivity, alkalinities, orthophosphate, nitrate-nitrogen, silicate, iron, filtrable dissolved solids, and occasionally for color, turbidity, calcium and total hardness, chloride, and sulfate. The techniques used were those of Standard Methods (Amer. Public Health Assoc., 1971). However, the method of Strickland and Parsons (1968) was occasionally used for orthophosphate, because of its greater sensitivity.

5. Temperature

Water temperatures were recorded on all sampling occasions at half meter depth intervals with one of the following electric thermometers: ET 100 Thermometer, Applied Research Austin Ltd.; RT 125 Marine Research Thermometer, Hydrolab Corp.; Model 54 dissolved oxygen and temperature meter, Yellow Springs Instruments Ltd.

6. Light

Secchi disc visibility was recorded at all stations sampled on each visit with a standard 20 cm diameter black and white Secchi disc. When desired, light penetration into the water column was measured with a submarine photometer (G.M. Mfg. and Instument Corp.) having both sea-cell and deck-cell selenium photocells. This gave results for light penetration into the water column in terms of both percent penetration of incident light and in approximate absolute units (foot candles). During winter, light penetration through the ice and snow cover was measured by mounting the photometer on the front of the ice jigger (Plate 4) and jigging the assembly away from the sampling hole to an area of undisturbed ice and snow. The face of the photometer cell was thus positioned 2.6 cm beneath the undersurface of the ice. This method did not allow measurement of light penetration at other depths however.

RESULTS AND DISCUSSION-GENERAL

In this section of the results, characteristics of the main body of the lake, as represented by stations 19, SC, AB, and 6 (Figure 1) will be presented. A complete listing of all data from all times and stations is placed in the appendices for productivity, chlorophyll, Secchi, temperature, oxygen, and cell counts.

A. Physical-Chemical

1. Temperature

Temperatures ranged from 0°C under the ice in winter to a maximum of 23.5°C, recorded on August 16, 1971 at station 19. Maxima recorded in other summers were 22.0°C (station 4, surface) on August 5, 1970, and 21.4°C (station 19, surface) on July 5, 1972. These maxima were usually transitory, and generally found only at the surface of the water column. The upper temperature range for the whole column in the summer does not greatly exceed 20°C. Figure 3 presents vertical temperature profiles of the main lake for selected dates.

Due to the relative shallowness of the lake and its good exposure to frequent strong winds, wind mixing of the water column is thorough and allows only brief periods of weak thermal stratification during summer. Klarer (1973) pointed out that the lake undergoes rapid warming in spring, in contrast to a much slower cooling in the fall. Mean water temperatures of approximately 16°C are reached by the end of

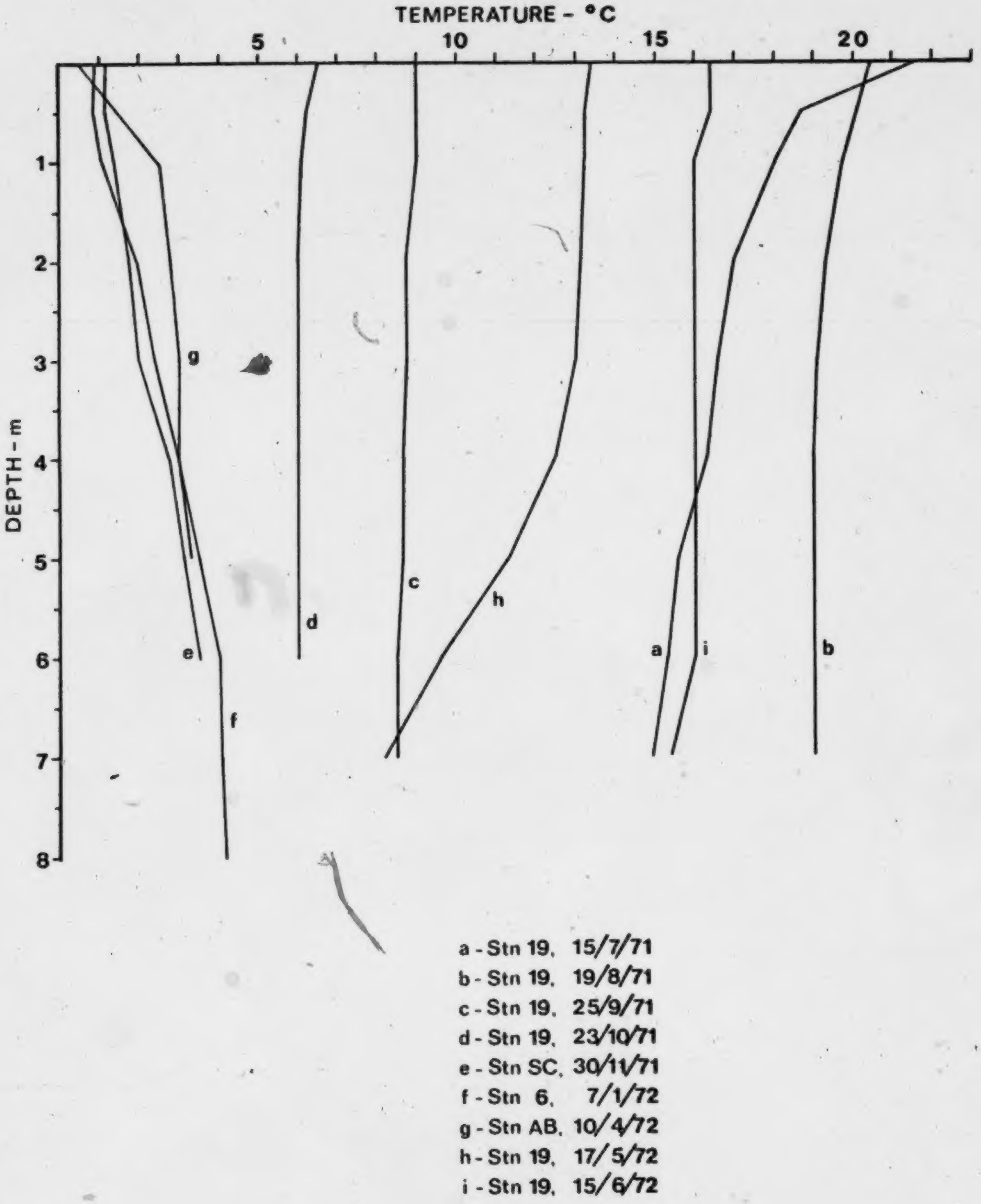


Figure 3. Vertical temperature profiles, 1971-72, at main lake stations.

May, approximately one month after break-up, while cooling in the fall over a similar temperature range takes approximately two months. At the time of spring break-up, the high air temperature, high solar radiation, and thorough mixing of the lake, allow for rapid heat transfer to the water.

2. Ice and snow cover

In general, freeze-up occurs in the first week of November, and ice is last seen in the two weeks around May first. The maximum ice depth recorded in this study (Table 2) was 70 cm. Horkan (1971) recorded maxima of 71.9 cm in 1969 and 71 cm in 1970. Unlike ice thickness, which slowly increases throughout the winter, snow depth on top of the ice is more variable, as a result of wind action and melting. Snow depth reached a maximum of 33 cm (Table 2) during the winter of 1971-72, while Horkan (1971) reported a maximum of 36.5 cm in the winter of 1968-69. The nature of the snow cover also varies as crystal structure changes, melting occurs, fresh snow falls, and wind packs the snow into hard drifts. Flooding of water on top of the ice, because of the weight of snow on the ice, can change the nature of the top layer of ice. The flooding water partially melts the snow cover forming a layer of slush that may freeze into a layer of cloudy ice. Further, because flooding can occur only where there are cracks in the ice to allow vertical movement of water, and because flooding water seeps slowly through the snow cover, horizontal variability in the nature of the snow and ice cover is to be expected. Snow drifting also produces horizontal variability. Some observations on this variability, as it affected light penetration through winter cover, are presented in Table 2.

TABLE 2

Ice and Snow Characteristics, Winter, 1971-72

Date	Stn	Ice Depth (cm)	Ice Nature	Snow Depth (cm)	Snow Nature	% Light Penetration
Nov. 30	SC	16	clear	0-10	drifts and clean ice	ice only-31 ice+snow-14
Jan. 1	Seba 6	45.5 54.0	clear top cloudy	10-15 14-20	hard drift hard drift	
Jan. 8	SC AB	48.7 48.0	 top cloudy	8-20 10-18	hard drift	
Feb. 20	SC	60	top cloudy	20-33	hard drift	
Mar. 7	SC	68	top cloudy	30		[1] 2m 0.09 5m 0.02 7m 0.04 10m 0.06 11m 0.06 13m 0.05 mean 0.05
Mar. 15	AB	67	top cloudy	25	crust on top+2cm of slush	[2] range 0.5-1.0 mean 0.7
Apr. 10	AB	70	top spongy and porous	1	thin crust	[3] range 9.0-15.0 mean 12
May 2			candled			

[1] Horizontal distance from sampling hole

[2] 14 Readings at meter intervals horizontally from hole

[3] 6 readings at two meter intervals horizontally from hole

3. Secchi Visibility

Values for Secchi disc visibility, a measure of the turbidity of the water, are plotted in Figure 4. The approximate mean summer value for 1971 was 1.7 meters. Visibility increased through fall and winter, to a maximum of 4.5 meters under ice and snow in early January, 1972, then decreased to lows of about 2.0 meters in the ice-free season of 1972. It would seem that maximum turbidities occur from late July to early September in Lake Wabamun. Both Horkan (1971) and Wheelock (1969) found a similar pattern of turbidity in the lake.

4. Light

Only white light was measured with the submarine photometer. Figure 5 presents curves of penetration of light into the water column on selected dates during the ice free season. On three of the four dates for which data are presented, the depth of 1% light penetration is between 6.0 and 7.5 meters. Judging by the corresponding values for Secchi disc visibility on these dates and at other times during the summer, this would seem to be representative of the light regimes during the June to September period of the year. The fourth curve, from May 17, 1972, shows higher penetration. Turbidity was low at that time.

The effects of ice and snow cover on penetration of white light into the water column are presented in Table 2. Obviously, the nature of the ice and snow cover is the

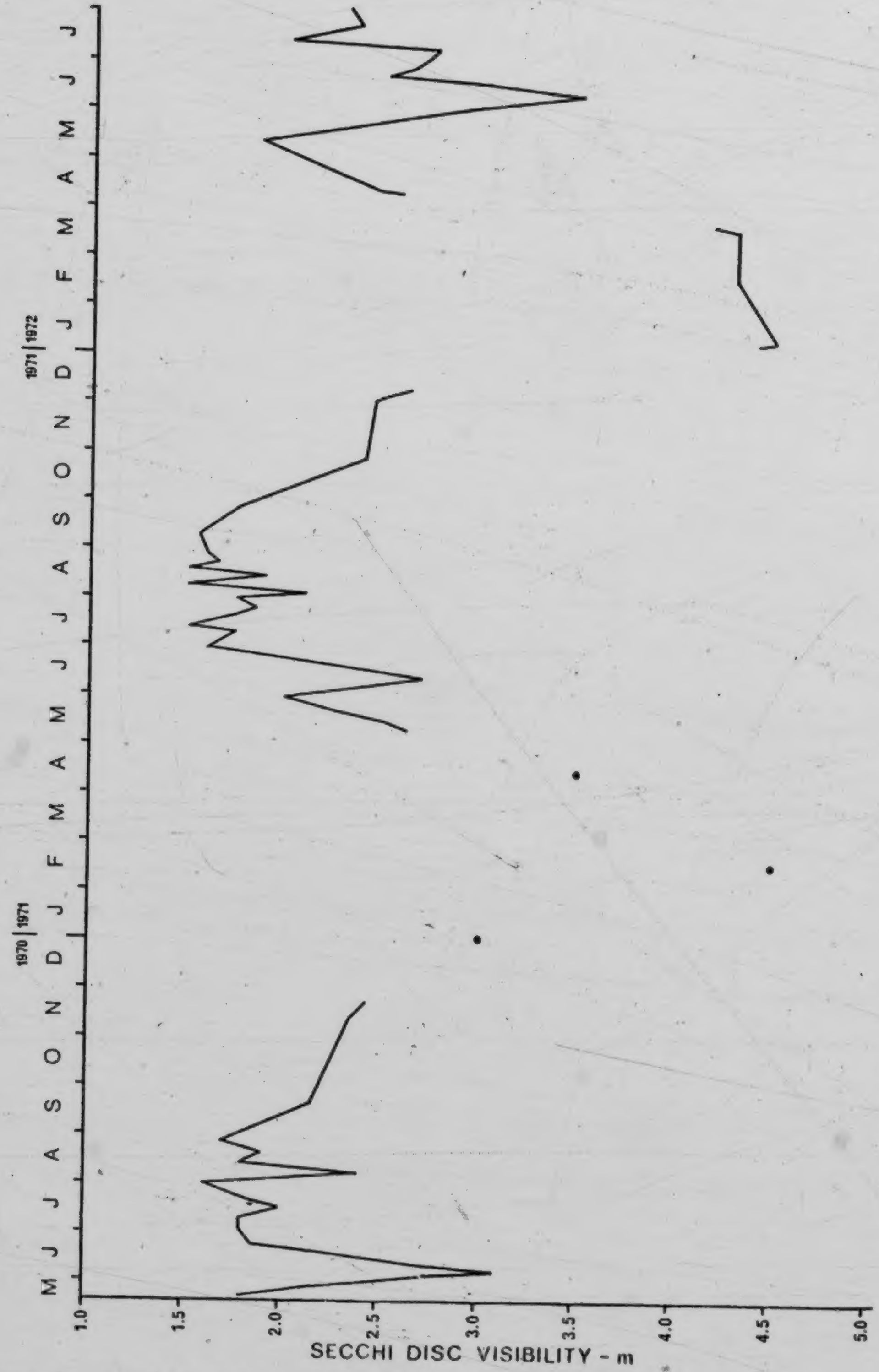


Figure 4. Secchi disc visibility, 1970-72, at main lake stations.

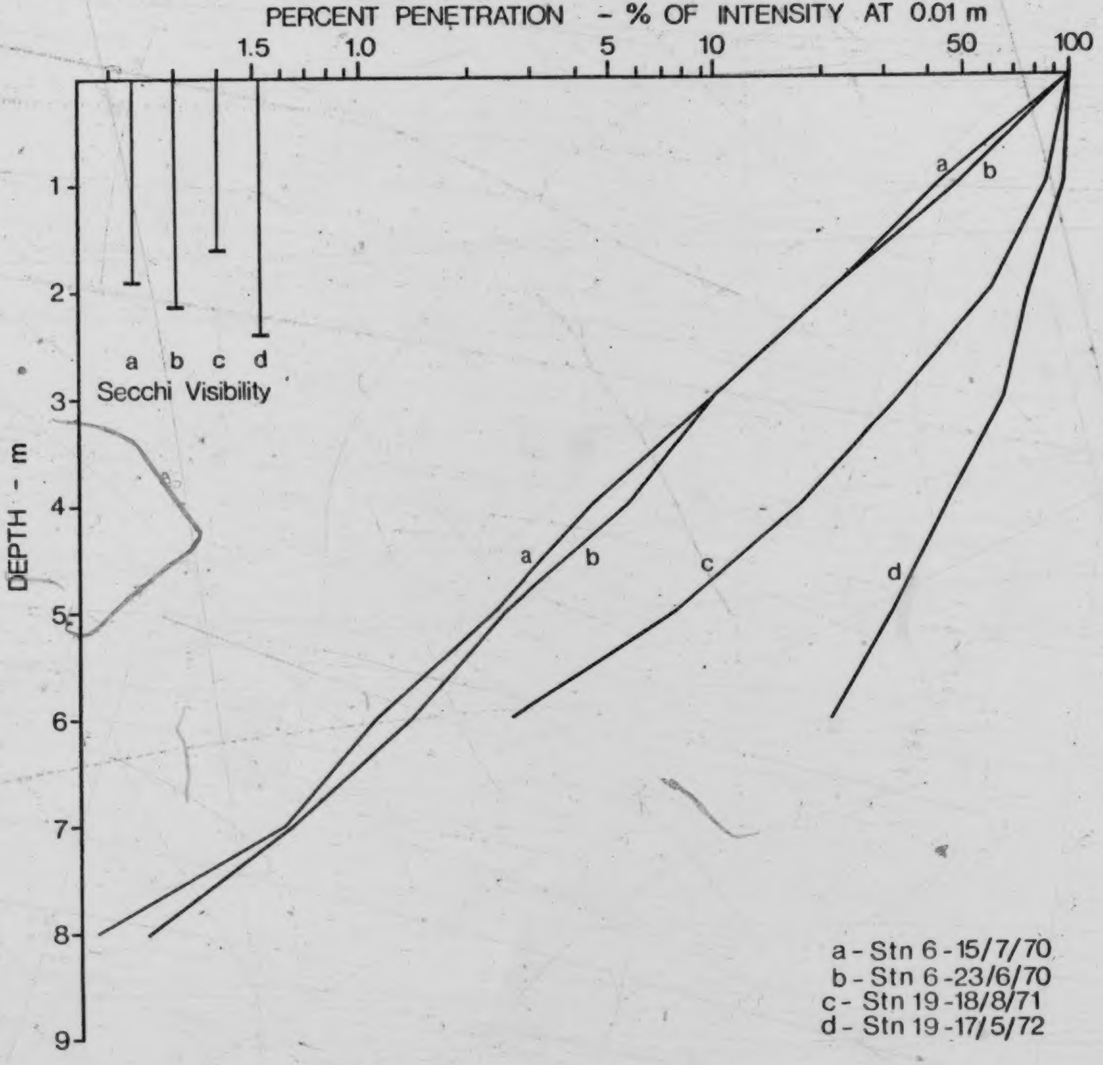


Figure 5. Penetration of white light at main lake stations.

governing factor determining percentage light penetration into the water column in winter. The spectral composition of this light does not seem to be affected by passage through the ice and snow (Allen, 1973; Greenbank, 1945). The percent penetration measured in this study varied from a high of 31% through 16 cm of clear ice to a low of 0.05% through 68 cm of partly cloudy ice covered by 30 cm of hard packed snow. Snow cover affects light penetration more than does ice cover. Greenbank (1945) noted this as well, suggesting that the albedo of the snow accounts for much of the light loss. He presents an excellent section on the characteristics of light penetration of ice and snow cover. Horizontal variability in the penetrability by light of the ice and snow cover can be seen in Table 2. Differences in percentage penetration over a horizontal distance of as little as 14 meters may approach an order of magnitude. Snow drifts, differential ice transparencies, and the presence or absence of slush, are factors that may be responsible for this.

5. Water Chemistry

Annual means and ranges of values for several chemical parameters at different sampling stations are presented in Table 3. Lake Wabamun can be characterized as a hardwater, bicarbonate lake. From the water chemistry data collected, seasonal cycles are evident in very few of the parameters. pH tends to be highest in summer and lowest in winter, but the difference is less than half a pH unit. Silicate is high in summer and winter, low in spring and fall. None of the other parameters show obvious seasonal fluctuations, although we might expect to see such fluctuations in orthophosphate, nitrate-nitrogen, and iron, with a more

TABLE 3

Water Chemistry

Annual means and ranges, June 1971-June 1972
Values from all depths and dates are included in means

Station-- Parameter	SI	SO	WI	WO[1]	SC[1]
pH	8.84	8.73	8.75		
	8.5-9.4	8.4-9.3	7.7-9.7		
Phen Alkal	11.7	9.7	11.8		
mg/l	5.2-19.9	1.5-19.0	0-28.0		
Total Alkal	172.9	173.2	176.2		
mg/l	157-184	117-197	142-199		
Phosphate,	0.012	0.023	0.019		
Ortho[2] mg/l	.003-.02	.003-.08	.003-.15	.015-.06	.012-.08
Silicate	1.5	1.79	1.92		
mg/l	0.8-2.75	<0.4-2.7	0.6-4.2		
Nitrate-N	0.04	0.04	0.04		
mg/l	.02-.14	.02-.09	.02-.10		
Conductivity	387	389	388	378	374
umho/cm	220-440	230-445	225-450	280-440	310-435
Filt Residue	229	235	229	231	237
mg/l	102-400	107-379	62.1-333	168-272	158-348
Iron	0.05	0.05	0.05		
mg/l	<.02-.18	.02-.47	<.02-.24		
Ca Hardness[3]	62	58	59	57	57
mg/l	54-80	50-66	50-66	48-62	52-64
Hardness,[3]	133	125	127	127	125
Total mg/l	100-192	100-144	104-152	112-144	104-168
Chloride[3]	2.3	2.0	1.9	1.8	1.8
mg/l	0.7-10.7	0.7-3.5	0-2.8	0.5-2.1	0.7-2.1
Sulfate[3]	30	31	30	29	29
mg/l	25-33	23-36	22-33	25-33	25-32

[1] Data from Gallup and Hickman, 1973

[2] Summer values used for means: winter method too insensitive

[3] Summer values determined only

thorough sampling program. The values in Table 3 for orthophosphate would tend to fit with those values given by Hutchinson (1957) and Vollenweider (1968) for moderately eutrophic lakes, however the values for nitrate-nitrogen, according to these same authors, indicate Wabamun is in a less productive trophic state.

B. Phytoplankton

1. Cell Numbers

Graphs of phytoplankton cell numbers at the surface and 1 meter depth of stations 19, SC, and AB, along with a graph representing ice and snow cover for the period of late June, 1971, to early August, 1972, are presented in Figure 6. The vertical distribution of the different phytoplankton groups was investigated for several dates throughout the above time period. Pronounced vertical stratification of the phytoplankton was never observed, even in winter samples, a result that agrees with Wheelock's (1969) observations. It is felt, therefore, that the cell numbers graphs for the above two depths give an adequate portrayal of the standing crop of phytoplankton cells present at these main lake stations. Appendix III contains a list of phytoplankton identified during the study.

Cell numbers were relatively low in early July, 1971. At that time, blue-green algae were numerically dominant in the phytoplankton and green algae were second in importance. During the rest of July, the total crop showed a general

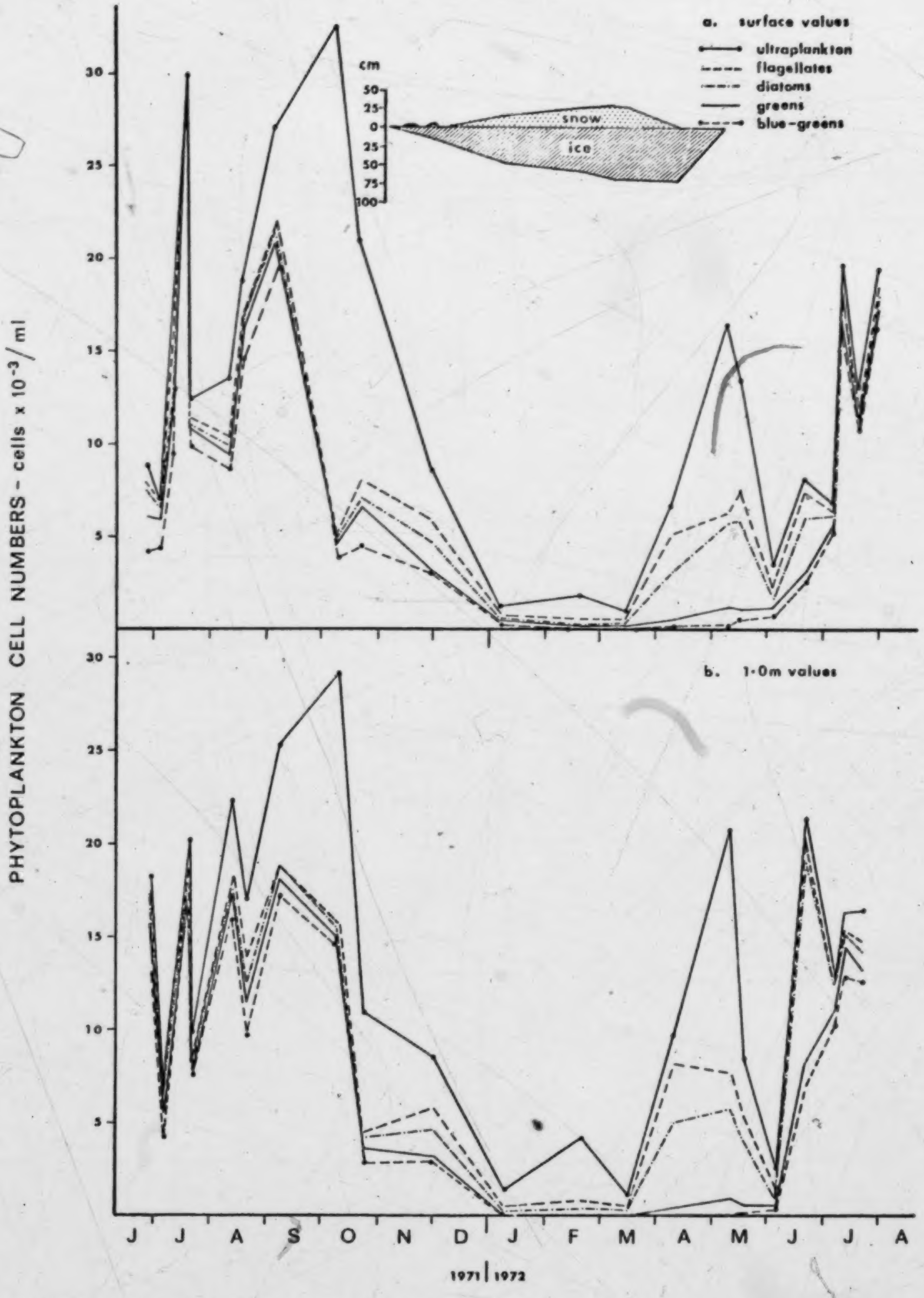


Figure 6. Phytoplankton cell numbers, 1971-72, at main lake stations.

increase which was largely due to an increase in blue-greens, but also composed of an increase in ultraplankton in late July. Both groups continued to increase throughout August, as did the total crop, which increased to a maximum of approximately 30,000 cells per ml in early October. This maximum was dominated by the ultraplankton; blue-greens peaked in early September and declined steadily thereafter.

Starting in early October, green algae, flagellates, and diatoms increased somewhat but then declined again through December to lows in early January, 1972. The ultraplankton showed a steady decline from early October to early January. Blue-greens declined through October, remained fairly constant in numbers during November, then almost disappeared by early January. The total cell crop declined precipitously from early October to a low of less than 1500 cells/ml in early January. The standing crop reached a minimum of less than 1100 cells/ml in mid-March. Ultraplankton dominated the winter populations, with the flagellates, and diatoms being important components as well. Green algae almost disappeared during this period.

Flagellates and diatoms began to increase in late March, peaked in early April, and then maintained high numbers until early May. Total cell numbers began increasing as well in late March, reaching a spring peak in early May, as did the green algae. In early April the ultraplankton began increasing, eventually forming around 50% of the spring peak in early May and dominating the phytoplankton community with the diatoms. Starting in mid May, the blue-green algae reappeared and increased exponentially in numbers to dominate the phytoplankton by late June, and to continue increasing in numbers and dominance through July, when they accounted for some 80% of all algal cells.

Total cell numbers declined sharply from early May to early June, largely as a result of precipitous decreases in ultraplankton and diatoms, although flagellates and green algae declined somewhat as well. Of these four groups, only the diatoms regained their importance in the phytoplankton before the end of this study, by accounting for a secondary peak in total crop in late June in conjunction with the blue-green algae. By early July, the diatoms had dropped to low abundances. Total cell numbers seemed to level off somewhat towards the end of July.

Comparing Secchi visibilities to phytoplankton numbers (Figure 17), it can be seen that there is a general correlation between the phytoplankton cell crops and the turbidity of the water. Both were at their highest levels in the July to September period and early May, and at their lowest levels in the January to March period of winter. Considering the low content of suspended inorganic solids in the lake, this relationship is to be expected. Also the ultraplankton, because of its small individual cell volume, contributes little to the turbidity of the water, as is apparent in the graphs for the September to November period of 1971. Horkan (1971) found a turbidity maximum (in JTU's) in the August to October period of 1968, and Secchi visibilities in early June, 1970, very similar to those found in this study in early June of 1972.

The influence of ice and snow cover on phytoplankton cell numbers is readily seen in Figure 6. In the fall of 1971, there was a precipitous drop in cell numbers in October but a more gradual decline during November despite the onset of ice cover on the lake. When snow cover appeared on the ice in December, algal populations declined more rapidly to lows in early January, 1972, and stayed at low levels until the snow cover disappeared in early April. Despite the fact that the ice was at its maximum thickness at the same time, the phytoplankton began its spring outburst as soon as the snow cover disappeared. Snow cover has been considered the main determinant in light penetration into the water column through a snow and ice cover (Table 2) and thus it appears to regulate winter and spring phytoplankton populations as well. Ice cover by itself does not seem to inhibit algal growth significantly since the spring outburst started under thick ice and peaked just as the ice cover disappeared.

It is thought that turbulence and mixing in a lake decrease sharply after freeze-up because wind action, the main cause of turbulence (Hutchinson, 1957), is shut off from the water. Consequently, horizontal and vertical heterogeneity in the plankton may increase. As was stated previously, vertical phytoplankton heterogeneity was not pronounced at the stations sampled in this study during the 1971-72 winter period of ice cover. This may be partly a result of as yet unknown currents in the lake. Horizontal plankton heterogeneity was not investigated in the winter, however, and so it is difficult to judge how representative of the whole lake the sampled stations are in the winter.

Green algae and flagellates were, numerically, relatively unimportant members of the phytoplankton. Together, they never comprised more than 50% of the total phytoplankton crop, even in winter, and although they occasionally showed population changes of an order of magnitude in less than a month, the maximum standing crop of either group was 3400 cells/ml for the green algae on July 11, 1971. Ultraplankton and blue-greens accounted for most of the phytoplankton for most of the year; blue-greens dominated from early July to late September, and ultraplankton dominated from late September to mid-March and then again briefly in late April and early May. Diatoms showed only two brief periods of dominance, in April and in late June. They maintained low populations throughout the rest of the year although they increased somewhat in November and December of 1971.

The genera Crucigenia, Oocystis, Pediastrum, Scenedesmus, and Tetraedron were common green algae. Asterionella, Fragilaria, Melosira, and the centric diatoms typified the diatom assemblage.

Blue-green algal blooms seem to be non-existent or at least extremely rare in Lake Wabamun. Although Carefoot (1959) stated that the lake blooms regularly, he gave no supporting evidence, and it is difficult to see how he arrived at his conclusion. Wheelock (1969) found no blooms during his study, and during the summers of 1970, 71, 72, in this study, no blooms were noted. The nearest thing to a bloom found in this study was the occurrence of a high blue-green population (over 27,000 cells/ml) containing numerous colonies of Anabaena sp. (probably A. flos-aquae (Lyngb.) de Brébisson) near the surface of the water column on July 19, 1971, following a few days of warm, calm, sunny weather. However, this was a brief phenomenon, it did not cause any obvious adverse effects, did not form a thick surface layer, and was only observed once. The blue-greens in general had the typical pattern (Reid, 1961) of a late summer maximum.

The ultraplankton is a difficult group to deal with. It is defined by cell size and general featurelessness which makes identification difficult. It does not include all the small plankters in this study because when algae in this size range could be identified, they were put in one of the other four groups; for example, the species of Rhodomonas were placed in the flagellate group although they were sometimes less than 5 μ long. Since the taxonomic status of the ultraplankton is unclear and probably not uniform (the group may contain both green and blue-green algae) it is hard to assess its response to environmental factors. Numerically, it is an important component of the phytoplankton, but its contributions to productivity and total chlorophyll a, and susceptibility to zooplankton grazing, are unknown.

Winter populations during the period of snow cover were composed largely of ultraplankton and flagellates. Both groups are well adapted to maintain their position in the water column; the ultraplankton by their small size (Hutchinson, 1967) and the flagellates by their motility; consequently they apparently are able to overcome the increased settling rates which occur under ice cover when turbulence is minimal. Diatoms are not unimportant at this time as well, suggesting that they also can resist increased settling rates.

Fogg (1965) described the typical succession of phytoplankton in freshwater temperate lakes as consisting of low winter populations, a spring diatom peak, low summer populations, and then a fall diatom peak. This is apparently meant to apply to lakes perhaps more oligotrophic and deeper than Wabamun, in which a thermocline is established in early summer and forms a nutrient trap for sedimenting phytoplankton such that there is nutrient depletion in the photic zone in the summer lasting until fall overturn. Wabamun does not stratify and is moderately eutrophic, thus, a summer phytoplankton population of blue-green algae can develop to peak populations in late summer. Hutchinson (1967), however, notes that, in general, shallower and more productive lakes tend to have significant blue-green populations which show late summer maxima, a finding which describes the situation in Lake Wabamun well.

Wheelock (1969) studied the phytoplankton of Lake Wabamun from spring, 1968, to spring, 1969. He also noted a gradual build-up of blue-green populations through the summer to maximum levels in late summer and early fall. His maximum total population size however, was 74,568 cells/ml in September, 1968, a value more than twice the maximum found in this study in October, 1971. Such differences in cell numbers are to be expected from year to year (Ruttner, 1961) and most likely do not indicate great changes in the phytoplankton characteristics of the lake. Total cell crop throughout the year showed some differences between the two studies, because Wheelock did not report any definite spring peak in cell numbers. Rather he found an irregular but overall increase from May to the end of July, then a dramatic rise to quite high levels which were maintained well into November, somewhat longer than in this study. Also, cell crops under the ice dropped to undetectable amounts from mid January to mid March, while in this study low but easily detectable numbers were found in the same period of 1972. Further, his findings revealed only a gradual increase in total cells from mid-March to early May, but in this same period in 1972, a spring outburst was occurring. These latter two discrepancies between the studies may be partly owing to the different positioning of the respective sampling stations. Wheelock's station 2 was in the extreme west end of the lake, while the stations in this study to which it was compared (stations SC and AB) were about one-half mile (3/4 km) off the north shore in the mid section of the lake, and may have been more influenced by currents generated by the thermal effluent. Such currents could have imported phytoplankton that had developed in the ice-free area.

The green algae showed similar importances in both studies, generally comprising less than 10% of total cell numbers. Wheelock did not differentiate a group of flagellates per se, but used the groups Pyrrophyta, Chrysophyceae, and Euglenophyta, which would be somewhat similar to the flagellate group reported here. He found them to be significant members of the phytoplankton only in May of both years, however, this study showed they were significant members from mid-November, 1971, until mid-June, 1972. The difference may be the result of the apparent absence of the Cryptophyceae in Wheelock's samples. This will be discussed later.

Diatoms were found to be major constituents of the April-to-June phytoplankton in both studies. However, as opposed to Wheelock's findings, which showed unimportant levels of diatoms in the rest of the year, a minor pulse of diatoms (up to 16% of the total crop) occurred in November, 1971. Diatoms maintained approximately this level of importance through the winter, until they further increased in spring, 1972.

The importance of the Cyanophyta to the Lake Wabamun phytoplankton is well demonstrated by both studies, although blue-greens were more dominant and abundant in 1968-69, than in 1971-72. Blue-greens formed similar percentages of total cell numbers through May to July of both studies, but Wheelock found that they became even more important (up to 98.9% of the total number) in the August to December period and apparently maintained this importance through the winter until late April. This dominance was largely the result of large populations of Lyngbya limnetica, a species found to be of minor importance in 1971-72. Blue-greens in general became sub-dominant by mid-October of 1971, disappeared in January of 1972, and did not reappear until May of 1972.

Wheelock did not report on any group of phytoplankton comparable to the ultraplankton studied here. Presumably, he included these small plankters in the other taxa.

The blue-green algal community in Lake Wabamun was dominated, in numbers, during the May to October period of 1971, by species of Anabaena, Coelosphaerium, and Aphanocapsa. Lyngbya limnetica was the dominant blue-green during the October, 1971, to early January, 1972, period. This is in contrast to the 1968-69 phytoplankton community, in which L. limnetica dominated the blue-greens from late July, 1968, to early January, 1969, and then again in April and May, 1969 (Wheelock, 1969). Also, Wheelock found only traces of Anabaena during his study, but it was an important member of the blue-greens at times during this study

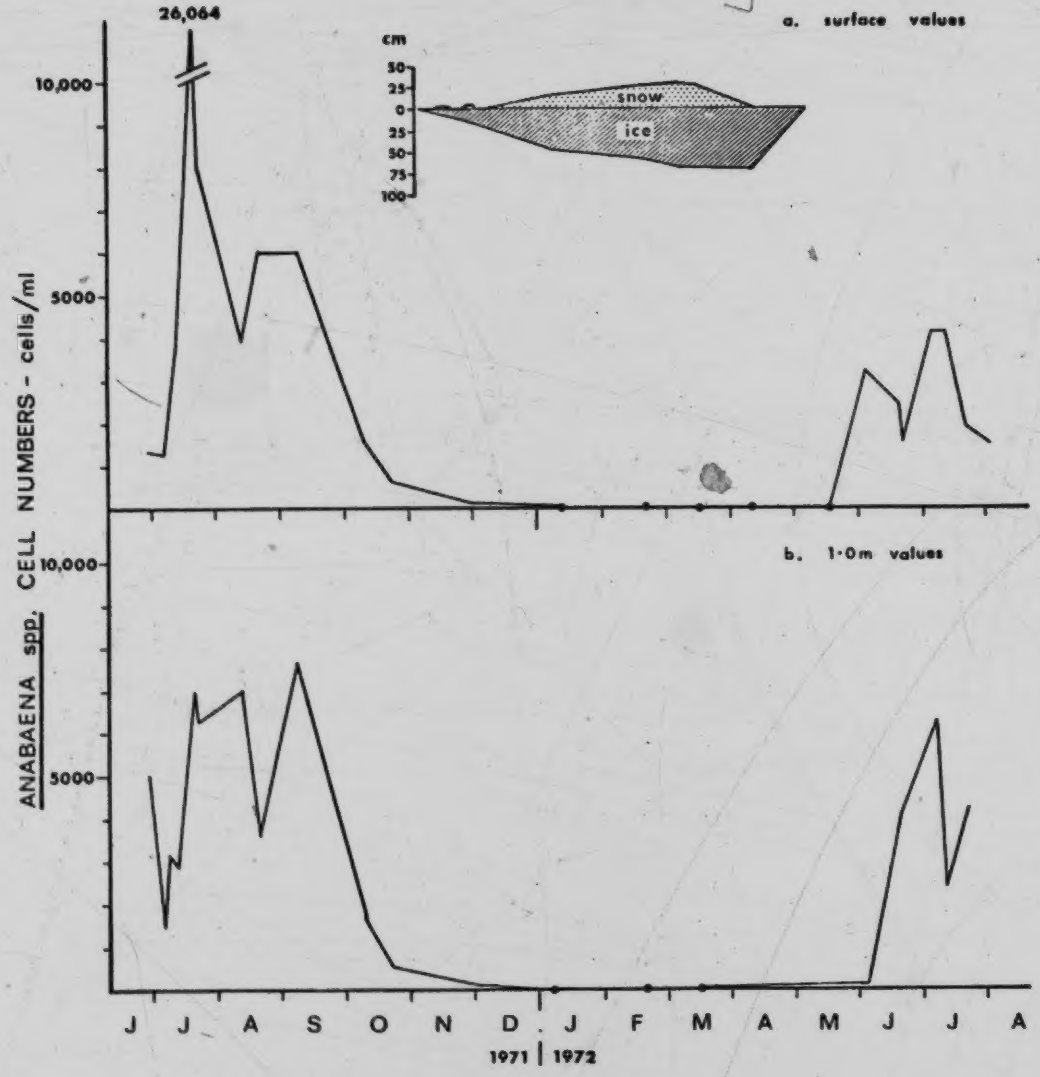


Figure 7. Anabaena spp. cell numbers, 1971-72, at main lake stations.

change in dominant blue-green species between the two studies is not too surprising because both studies lasted little more than a year, and differences in species composition between years are commonly reported in the literature. Wheelock noted that Carefoot (1959) found blue-green species somewhat different from those of either of these latter two studies. Graphs of cell concentrations of Anabaena spp. throughout the 1971-72 study are presented in Figure 7. Anabaena shows a periodicity somewhat similar to the blue-greens in general, but which declines somewhat earlier in the fall, and has an early summer peak in 1972 almost as great as the late summer peak of 1971.

Cell numbers of the Cryptophyceae are presented in Figure 8. This group, consisting largely of the genera Rhodomonas and Cryptomonas, was not reported by Wheelock, probably because of his sampling and counting methods. He took qualitative samples using a #20 net which would, very likely, have missed the Cryptophyceae because of their relatively small size. For his quantitative analyses, he concentrated the phytoplankton using a centrifuge, a process that may well have ruptured these delicate algae.

The Cryptophyceae show an interesting periodicity. They had two main peaks of abundance, one occurring immediately after freeze-up, 1971, the second immediately before break-up, 1972. The intervening lower populations occurred during the time of snow cover in winter, and during the summer ice-free season. This strongly suggests that this group, because

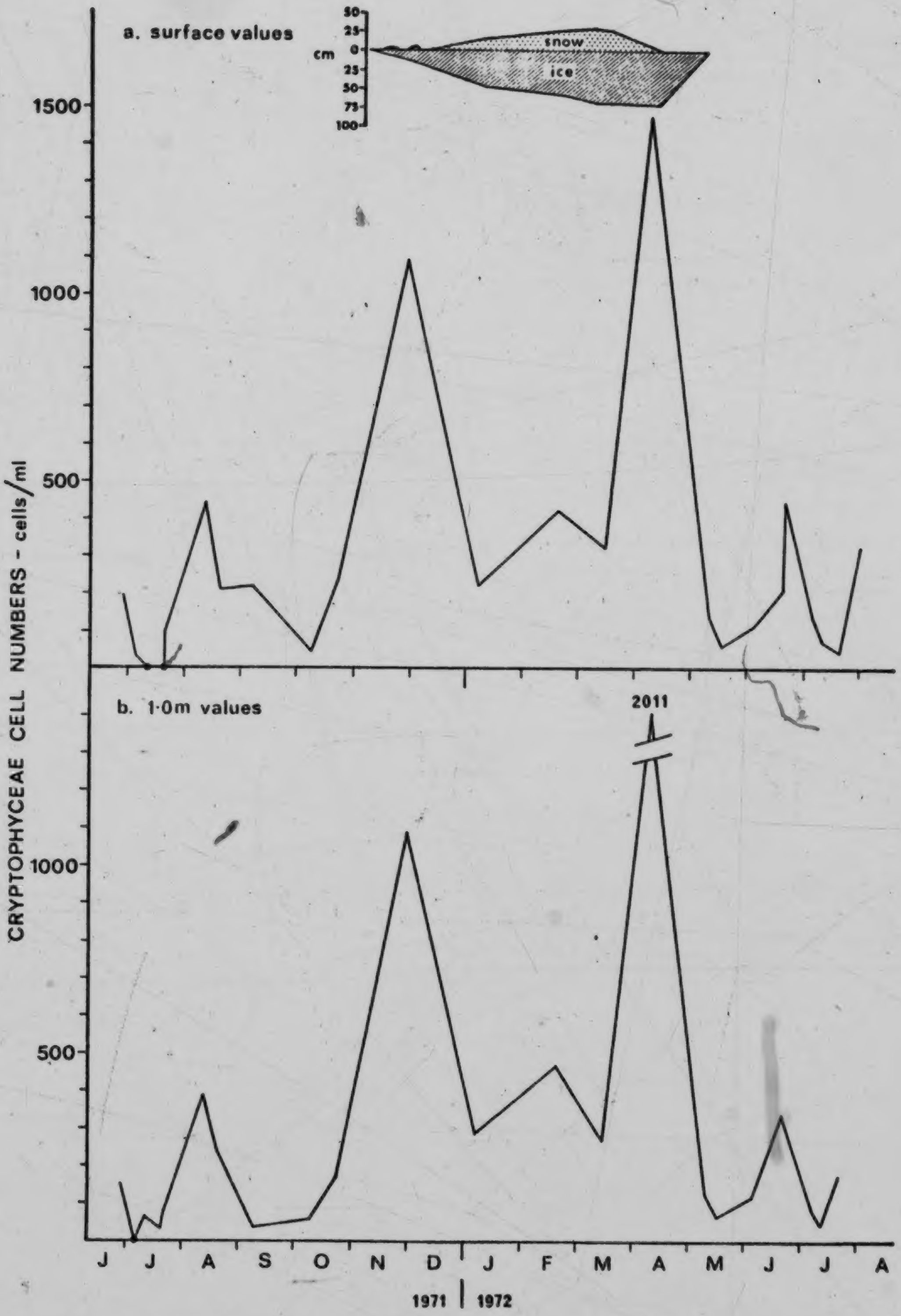


Figure 8. Cryptophyceae cell numbers, 1971-72, at main lake stations.

of its motility, has a competitive advantage over other phytoplankton during the period of minimal water turbulence. Their motility would allow them to maintain their positions in the water column under conditions of increased settling rates that could deplete populations of other non-motile plankters. The period of snow cover coincided with low levels of this group, presumably because of the effect of snow cover in strongly limiting light penetration into the water. Although Wheelock did not note the occurrence of this group in Lake Wabamun, Bozniak (1966) found members of the Cryptophyceae to be common during the winter in two other central Alberta lakes.

2. Chlorophyll a

Values for chlorophyll a in milligrams per cubic meter are presented in Figure 9, for the stations in the main body of Lake Wabamun. These values are means of the different depth values determined for each date plotted; thus, they are representative of water columns of different depths. Considering the lack of vertical stratification in the lake, the plotted values are felt to be representative of actual conditions.

The maximum recorded mean value for chlorophyll a was 16.4 mg/m³ on August 18, 1971, and the minimum mean value was 1.0 mg/m³ on March 15, 1972. Values for any one particular depth reached a maximum of 19.1 mg/m³ at a depth of 0.5 m, on July 21, 1971, and a minimum of 0.8 mg/m³ at

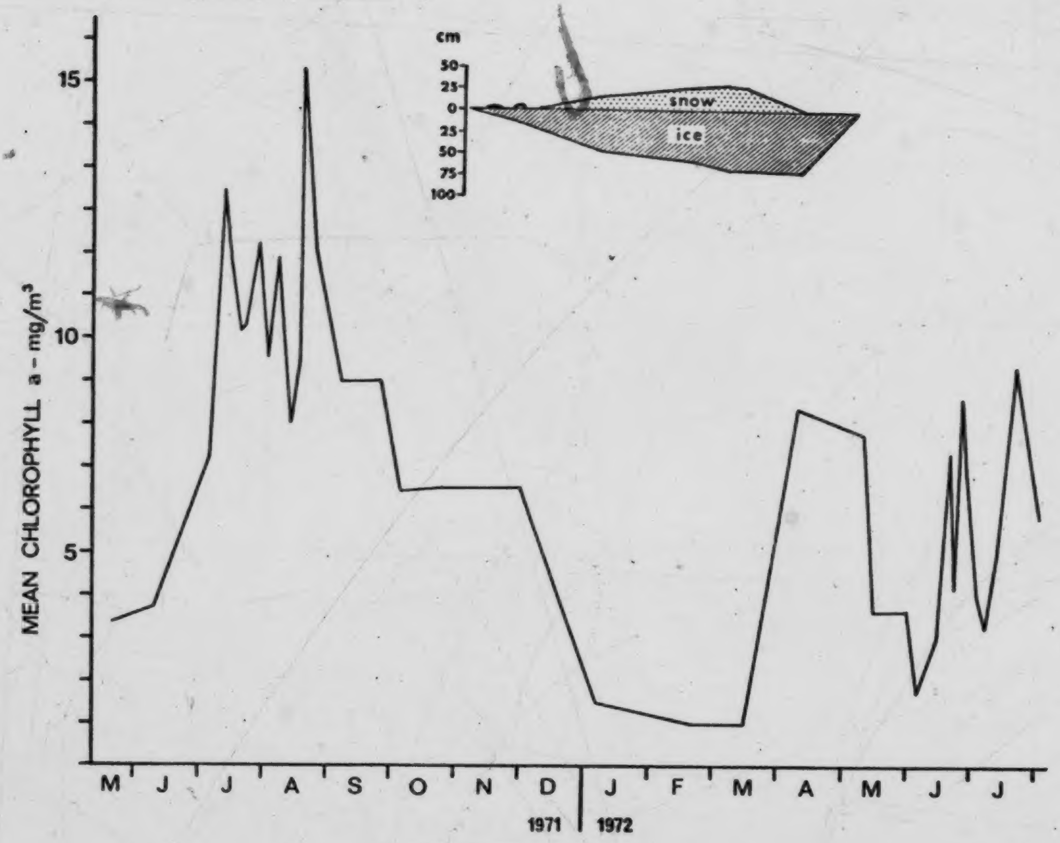


Figure 9. Mean chlorophyll a concentrations, 1971-72, at main lake stations.

0.5 m depth on March 15, 1972.

The plot of mean chlorophyll a concentrations closely follows the plots of total cell numbers (see Figure 17). From fairly low values in late May and early June of 1971, values rose exponentially through June and early July to summer levels in mid-July of about 11 mg/m³. This concentration was maintained, in general, throughout the rest of July and until the end of August. Chlorophyll a declined through September to a level of 6.5 mg/m³ in early October, then remained fairly constant until the onset of snow cover in mid-December, when chlorophyll levels again dropped, reaching their low winter level of about 1.5 mg/m³ in early January, 1972. As with phytoplankton numbers, chlorophyll a showed a dramatic response to snow cover on the ice: it dropped to its lowest level when the snow appeared in mid December, 1971, and stayed low until the snow disappeared in late March, 1972. This was undoubtedly because of the low light levels in the lake at that time. During the spring phytoplankton pulse, chlorophyll levels remained closely correlated with cell numbers, rising in late March and early April to concentrations of about 8 mg/m³, then declining in mid-May to lows in early June. As with cell numbers, there was a peak in late June, a low in early July, and then somewhat higher levels in August. Unlike cell numbers, however, chlorophyll did not reach values in July, 1972, comparable to those of July, 1971. The former were about 6 mg/m³, while the latter were about 9 mg/m³.

Lake Wabamun would seem to have chlorophyll values corresponding to those of a moderately eutrophic lake. Sakamoto (1966), cited in Vollenweider (1968), gives ranges of chlorophyll values he considers typical for lakes of different trophic condition. Wabamun had a mid-summer chlorophyll a content of about 11 mg/m³. The mean depth of the lake is 5.4 m, thus the mean chlorophyll concentration per unit surface area for the lake as a whole is 59 mg/m². These values are midway between those of Sakamoto for mesotrophic and eutrophic lakes. Aruga and Monsi (1963) suggest a concentration of 30 to 120 mg/m² for eutrophic lakes, a range that includes Lake Wabamun in its lower half.

Canadian Shield lakes can generally be considered more oligotrophic than Lake Wabamun, and according to Schindler (1972) chlorophyll values are generally lower as well. He gives mean summer values for two lakes in the Northwest Territories, several lakes near Kenora in northwestern Ontario, and two lakes in southeastern Ontario. Only four lakes in the Kenora area had chlorophyll contents higher than L. Wabamun. Chlorophyll data for Canadian prairie lakes are not abundant, although Hamilton (1963) gives values for four southern Saskatchewan lakes, near Saskatoon, that are somewhat more eutrophic than L. Wabamun. These lakes had summer chlorophyll concentrations of about 25 mg/m³. Barica (1973) gives chlorophyll values approaching 100 mg/m³ for four small, highly eutrophic lakes in southwestern Manitoba.

Finally, D.N. Gallup and M. Hickman (pers. comm.) report summer chlorophyll values, in other central Alberta lakes (Buffalo, Gull, Pigeon, and Sylvan) ranging from 2.5 to 11 mg/m^3.

3. Phytoplankton Productivity

Phytoplankton productivity values were initially calculated from the raw incubation data in units of $mgC/m^3/hr$. Graphs of values in these units for two depths at main lake stations are presented in Figure 10. These values are calculated from results of midday incubations with the C^{14} method in 1971 and 1972. Both curves have similar shapes but different absolute productivity values, those of the 1.0 m depth being greater. The maximum carbon assimilation value recorded was 115.8 $mgC/m^3/hr$ on August 18, 1971, at a depth of 0.5 m. Productivity fell to levels below detection at all depths during the winter of 1972. The pattern of productivity through the 1971-72 sampling period, illustrated in Figure 10, was one of relatively high levels of productivity in the period July to early September, then decreasing values until early January, when productivity became undetectable and remained so until late March. A spring peak in productivity developed in early April, but soon declined to lower and fluctuating levels through May to July of 1972.

The vertical distribution of midday production in the water column in the main lake is graphically illustrated for

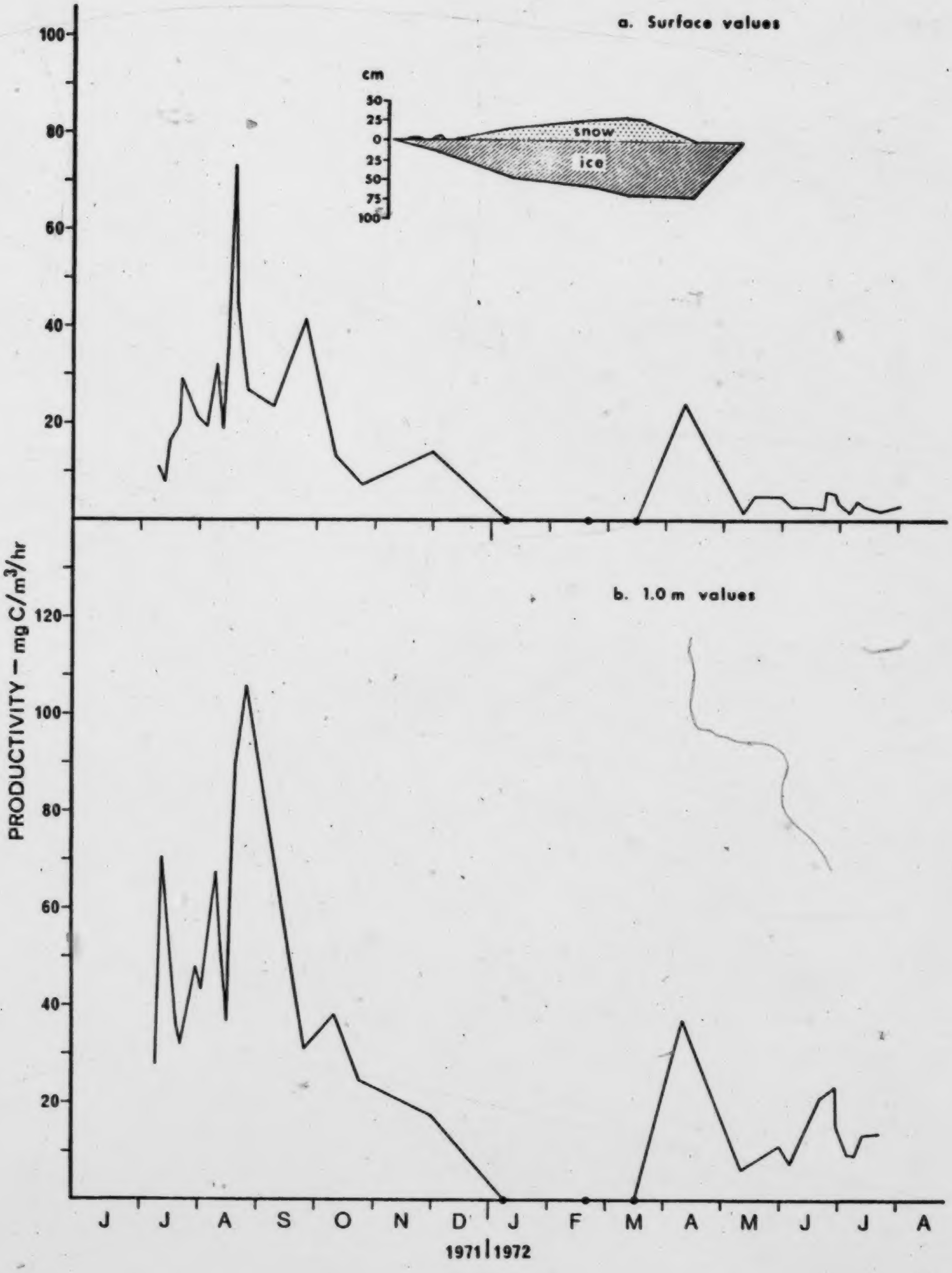
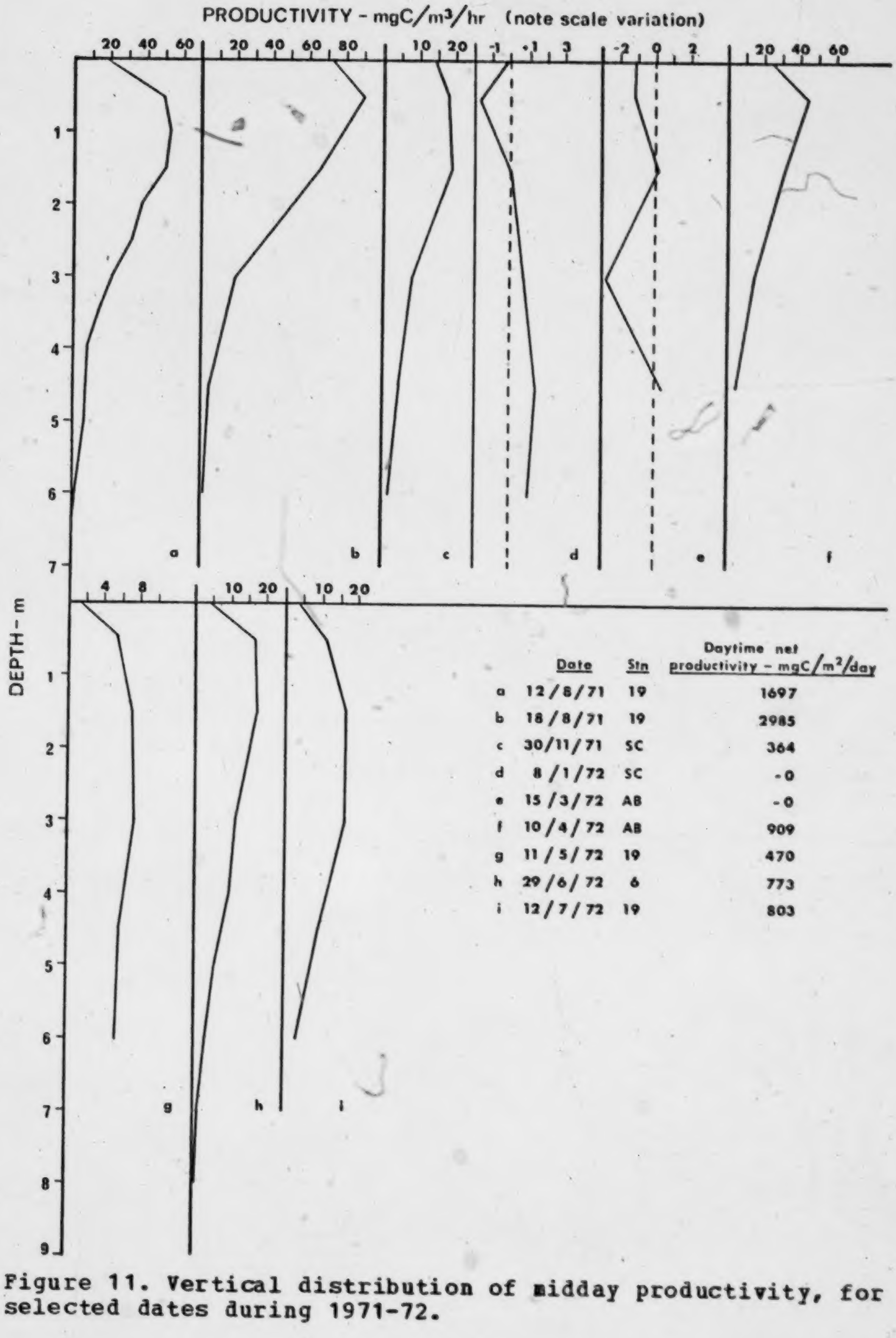


Figure 10. Midday phytoplankton productivity, 1971-72, at main lake stations.

selected dates in Figure 11. In August of 1971, production was concentrated in the top three meters of the water column and was negligible below a depth of six meters. In November, the vertical distribution was still largely the same, but productivity values were much lower. A surface decrease in productivity was evident in both of these graphs of midday productivity.

Under ice and snow cover, from early January to mid-March, productivity was essentially undetectable at all depths. Although values of up to 2 mgC/m³/hr were recorded during this period, negative values of up to 2.8 mgC/m³/hr were also noted, indicating that the methods employed were not adequate to measure production rates any less than about 2 mgC/m³/hr. Undoubtedly, there was some production during this period, however, it was not measurable and would have been negligible in relation to overall annual production. Curves of spring productivity under the ice are quite similar to those of August, 1971: productivity dropped to negligible values at a depth of 6.0 meters. In early May, however, the vertical distribution of midday productivity changed markedly: productivity was very similar at all depths measured; there was only slight inhibition at the surface; photosynthesis apparently could have extended much deeper than 6 meters if the water had been deeper. Curves for late June and mid-July, 1972, are more similar to those of August, 1971, in that maximal productivity occurred at about 1.5 meters and fell to lower levels by 6 meters.



	Date	Stn	Daytime net productivity - mgC/m²/day
a	12/8/71	19	1697
b	18/8/71	19	2985
c	30/11/71	SC	364
d	8/1/72	SC	-0
e	15/3/72	AB	-0
f	10/4/72	AB	909
g	11/5/72	19	470
h	29/6/72	6	773
i	12/7/72	19	803

Figure 11. Vertical distribution of midday productivity, for selected dates during 1971-72.

However, production was still not concentrated in the surface layers as much as in late summer of 1971.

The distribution of production throughout the day was investigated on three occasions in the 1971-72 period, using the C^{14} method. Stations and dates selected for this were station 19 on August 18 and 19, 1971, station KB on May 25, 1972, and station 19 on July 12, 1972. Figure 12 shows the diurnal productivity curves for these three dates, plus solar radiation values for the Stony Plain Meteorological Station. Doty and Oguri (1957) reported variability in the ability of oceanic phytoplankton to fix carbon at different times of the day, the ability being highest just before noon and lowest at about 7 PM. The three diurnal studies here do not show such a pattern, but indicate that there may be a slight early afternoon maximum in phytoplankton photosynthetic ability. The latter pattern was also noted by Donald (1971) in small ponds near Calgary and by Anderson (1974) in mountain ponds.

Figure 13 presents the vertical distribution of productivity for the seven incubation periods of the diurnal study on August 18-19, 1971. That was one of the most productive days on record.

To obtain an estimate of annual production for the main body of the lake, calculations were made based on results of the C^{14} method which had been used exclusively for more than a year. The C^{14} method measures something approximating net productivity (Ryther, 1956) so that these calculations

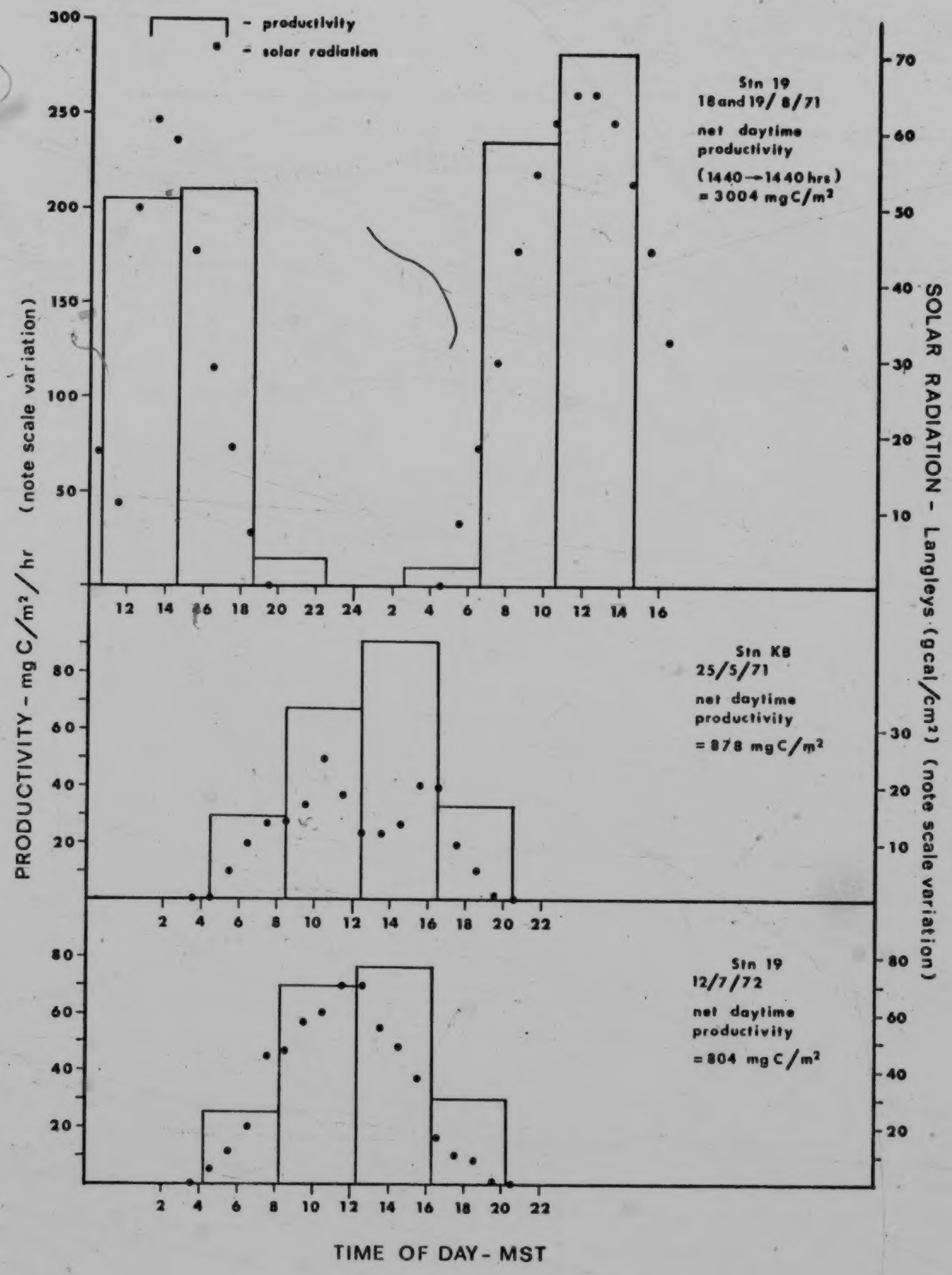


Figure 12. Diurnal productivity and solar radiation, on three dates, 1971-72.

give values for net production. Furthermore, because the C^{14} method provides no information concerning algal respiration, we can not obtain estimates of night or day algal respiration to allow for respiration in calculating 24-hour net production. Thus the C^{14} method allows us to calculate only an approximate value for daytime net production, a fact that most authors neglect to mention when reporting C^{14} productivities.

In calculating annual daytime net production from the results of this study, it was necessary to determine the distribution of photosynthesis both throughout the water column and throughout the day for the days when it was measured. In determining the former, extrapolation from incubation results in the surface waters was necessary because most incubations were confined to the top two meters of water, as the need for simultaneous incubations at two sampling stations did not allow complete vertical sampling. The vertical distribution curves (Figure 11) were consulted to give an estimate of the percentage production occurring in those surface waters investigated, and results for surface waters were then extrapolated to results per unit surface area (m^2) using these empirically determined percentages for production distribution. Vertical distribution curves from the same time of the year as the surface productivity results were used in these extrapolations. Thus, when the incubation for station 19 on September 8, 1971, showed that there was 91.7 mgC/hr in the

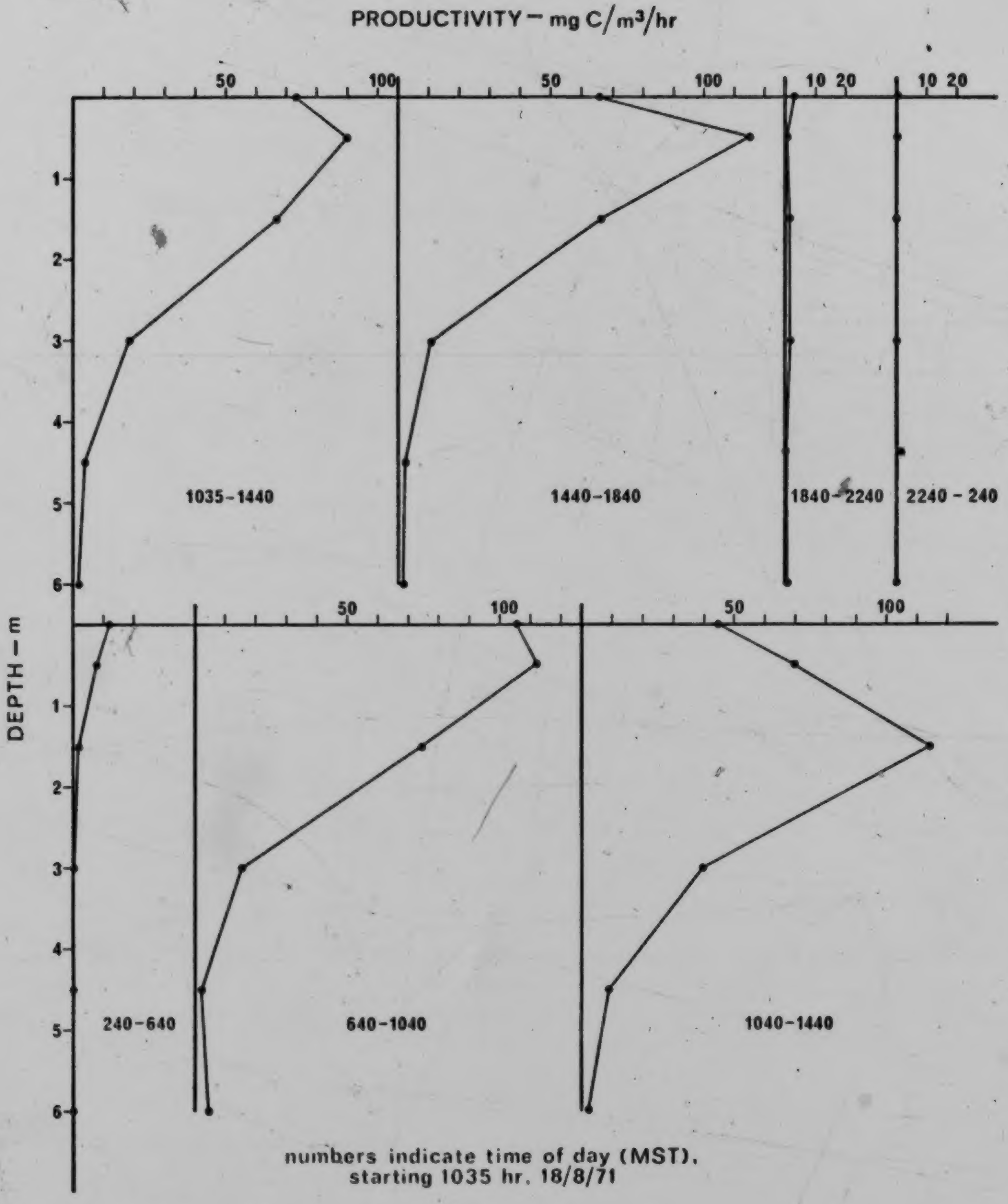


Figure 13. Vertical distribution of diurnal productivity at station 19, August 18-19, 1971.

top 2.5 meters (incubations having been done at 0, 0.5, 1.0, and 2.0 meter depths) during the midday period, and the vertical distribution curves for August 12, 18, and November 30, 1971, indicate that 76% of total production during the midday period occurred above 2.5 meters depth, we conclude that there was 121 mgC/m²/hr productivity in the 4-hour noon period of this date.

Next, it was necessary to extrapolate the midday values (mgC/m²/hr) to daytime estimates of production (mgC/m²/day). The three diurnal studies performed gave similar results for the proportion of daily production that occurred during the 4-hour midday period (1000-1400 hours). The mean proportion was 35%, the range being 33.5% to 36.5%. That these studies, conducted at three different times during the summer period, gave these very similar proportions is not surprising considering the relatively even distribution of total daily solar radiation throughout this period. Figure 14 is a graph of mean daily solar radiation in Langleys/day for the Stony Plain Meteorological Station, 15 miles east of Lake Wabamun (Environment Canada, 1971-73). The graph shows that mean daily solar radiation levels were very similar for the months of May, June, July, and August. Thus it was assumed that for all incubations performed during the May to August period, the midday results (mgC/m²/4hr) would be 35% of daytime production, and daytime production could be calculated accordingly. For dates outside this summer period the ratio Id/Ii (where Id is the total incident radiation

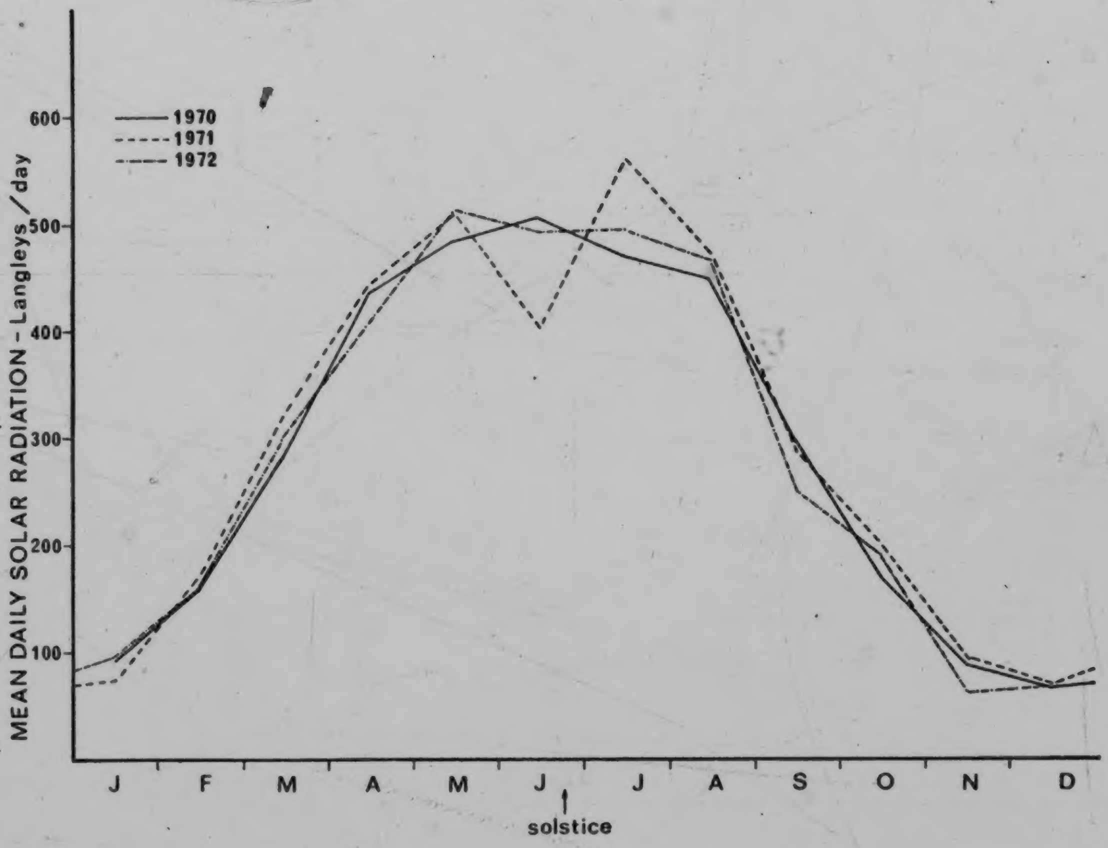


Figure 14. Annual distibution of daily solar radiation, 1970-72, at Stony Plain, Alberta.

during the day in question and Ii is the incident radiation during the four hour incubation period) was multiplied by the midday productivity value to obtain daytime net production. These values for incident radiation were also obtained from Environment Canada (1971-73) for the Stony Plain Meteorological Station. It is assumed that the station is close enough to Lake Wabamun to provide valid solar radiation data for the lake.

Anderson (1974) has criticised the use of Id/Ii in estimating daily production, and has shown that it misrepresented daily production in his studies largely because of light inhibition of productivity during the midday period. The three diurnal studies done here are in agreement with his finding that midday productivity is not proportional to midday solar radiation on sunny days. Also, increased reflection of sunlight from the water surface in early morning and late evening would give further inaccuracies in results. Despite the errors in this method, it was used for the September to April data, as there was no other method of estimating daytime production from the available data.

Net daytime production is plotted in Figure 15 for 1971-72 (C^{14} method) along with summer 1970 values for daily gross production (oxygen method) for the main body of Lake Wabamun. The annual curve of net daytime production is quite similar to that of annual volumetric productivity. This is expected because the values in Figure 10 were components in

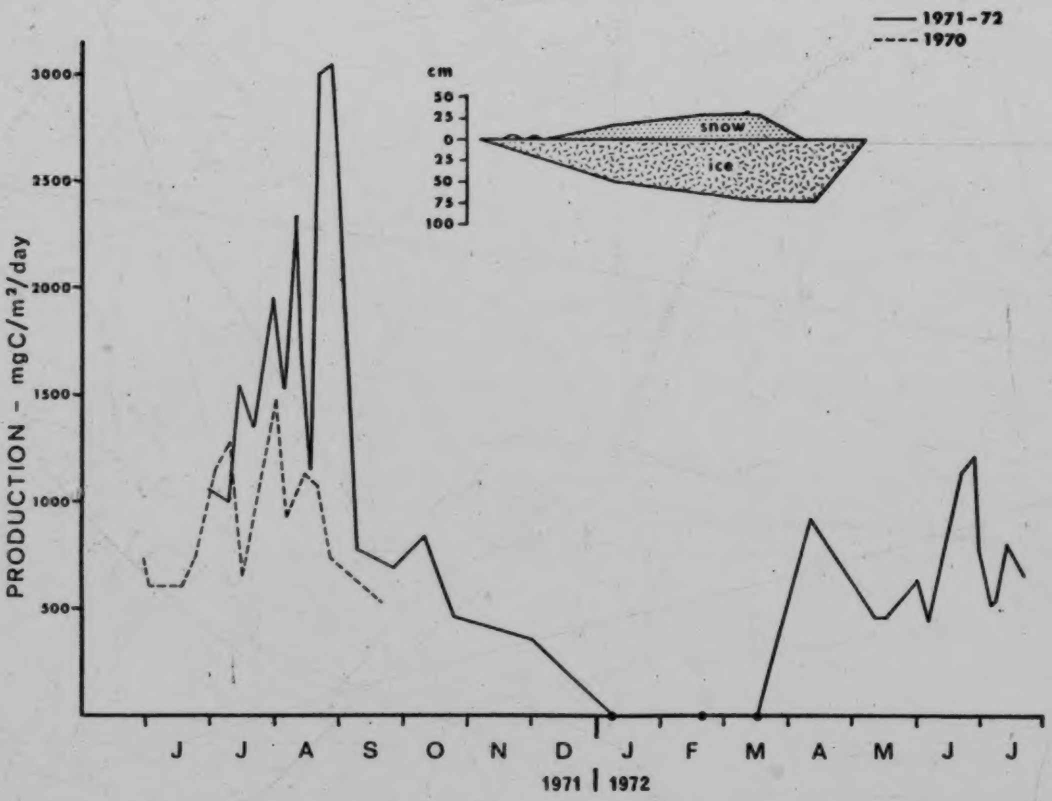


Figure 15. Phytoplankton production, 1970-72, at main lake stations. Gross production in 1970, daytime net production in 1971-72.

the calculations of values for Figure 15. The net daytime production for the main body of Lake Wabamun from July 10, 1971, to July 10, 1972, was calculated from Figure 15 by planimetry to be 170 $gC/m^2/yr$. A maximum individual daytime production occurred on August 25, 1971, and was 3,045 $mgC/m^2/day$.

Figure 15 also depicts gross daily phytoplankton production for the summer period of 1970, as measured with the oxygen method. Levels of productivity are comparable in the summer period of all three years, although in 1971, productivity was higher in the late July to end of August period. Approximate mean 1970 summer levels of gross production were slightly above 1000 $mgC/m^2/day$, a value which is similar in magnitude to results of 1971-72, although the latter is net production and the former is gross production.

The relationship of phytoplankton productivity to ice and snow cover is easily seen from Figure 15. A cover of ice by itself does not seem to markedly affect productivity, as productivity was quite significant in November, 1971, under 25 cm of clear ice and again in late March, 1972, under as much as 70 cm of clear and cloudy ice. During the period of ice and snow cover, however, productivity fell below levels of detection. This is not surprising considering the relative effects of snow and ice cover on the penetration of light into the water column (see Table 2). Schindler (1972), Schindler and Comita (1972), Pechlaner (1964), and Greenbank

(1945), found similar patterns of winter productivity: productivity can be quite significant under ice cover only but is markedly inhibited by snow cover on top of the ice. The differing influences of these two types of winter cover on light penetration is undoubtedly the controlling factor.

Phytoplankton cell numbers and phytoplankton productivity show a general correlation throughout the study as can be seen from Figure 17. Both parameters show general increases through July and August of 1971, productivity reaching maximum levels in the latter month. In September of 1971, however, productivity dropped markedly while cell numbers actually increased to maximum levels in early October, then declined steadily along with productivity, to winter lows in the January to March period of 1972. The ultraplankton composed large percentages of the fall cell crop maximum which may explain the poorer correlation between productivity and cell numbers at that time as small phytoplankton cells can be expected to contribute less to the overall productivity than a similar number of large cells (Fogg, 1965). There was a spring peak in both cell numbers and phytoplankton productivity in April, 1972, followed by fluctuating but generally lower levels of both from mid-May to early June. Cell numbers increased in July but productivity did not. Blue-green algae were responsible for the increase in cell numbers. This occurrence of relatively high blue-green numbers and low productivity contrasts with the occurrence of abundant blue-greens and high productivity in August of 1971.

Mean phytoplankton chlorophyll a concentrations (Figure 9) show a correlation with productivity similar to that of cell numbers with productivity (Figure 17). High values of both parameters were found in the July-August period of 1971, but chlorophyll values dropped more gradually through September than did productivity, and maintained constant levels in October and November when productivity was showing a general decline. Both declined markedly through December to lows in the January to mid-March period of 1972. A spring peak in April, lows in late May and early June, and a peak in late June, occurred in both parameters. Chlorophyll a values rose in July, 1972, as did cell numbers, but productivity did not rise.

The ratio of productivity ($mgC/m^3/hr$) to chlorophyll a content (mg/m^3) of the water has been termed the assimilation ratio by some authors (Curl and Small, 1965; Thomas, 1970; Eppley et al., 1973) or the photosynthetic index (Hickman, 1973). It has been suggested as an indicator of the nutrient deficiency of the phytoplankton (Thomas, 1970) when determined under light conditions optimal for photosynthesis. The ratio will depart from optimal (maximal) values under conditions of sub- or supra- optimal light. Given a fairly uniform vertical distribution of phytoplankton chlorophyll a, the vertical distribution curves of productivity and assimilation ratio will be approximately parallel (Curl and Small, 1965). During a year, the maximum assimilation ratio may be affected by unseasonably low temperatures, changes in algal species, low winter light levels, and deficiencies of nutrients.

Figure 16 presents a graph of maximum assimilation ratios that occurred on given dates in the water column, and the depth of this maximum, throughout the year. These values were determined from the standard midday incubations. The two values are not correlated nor should they be, since the highest ratios occurring in the water column will stay roughly the same during a period of the year (August, 1971, for example) but will move up and down in the water column in response to changes in incident radiation, which can be controlled by cloud cover. On any given day, the ratio will vary with the time of day and depth considered, as reported by Curl and Small (1965). Midday maximum assimilation ratios never occurred at the surface of the water in this study, indicating that there was always some light inhibition of photosynthesis at that time of the day. Assimilation ratios generally follow values for chlorophyll, productivity, and cell numbers through the year but do not show fluctuations as large as those of the other three parameters. Curl and Small (1965) found mean optimal assimilation ratios of 8.6 in the Pacific Ocean off Oregon, Thomas (1970) found optimal ratios of about 4 in the tropical Pacific, Eppley et al. (1973) recorded maximum ratios of from 4 to 8 in the North Pacific, and Hickman (1973) found surface values up to 8.5 and a mean value of 1.43 in a small English lake.

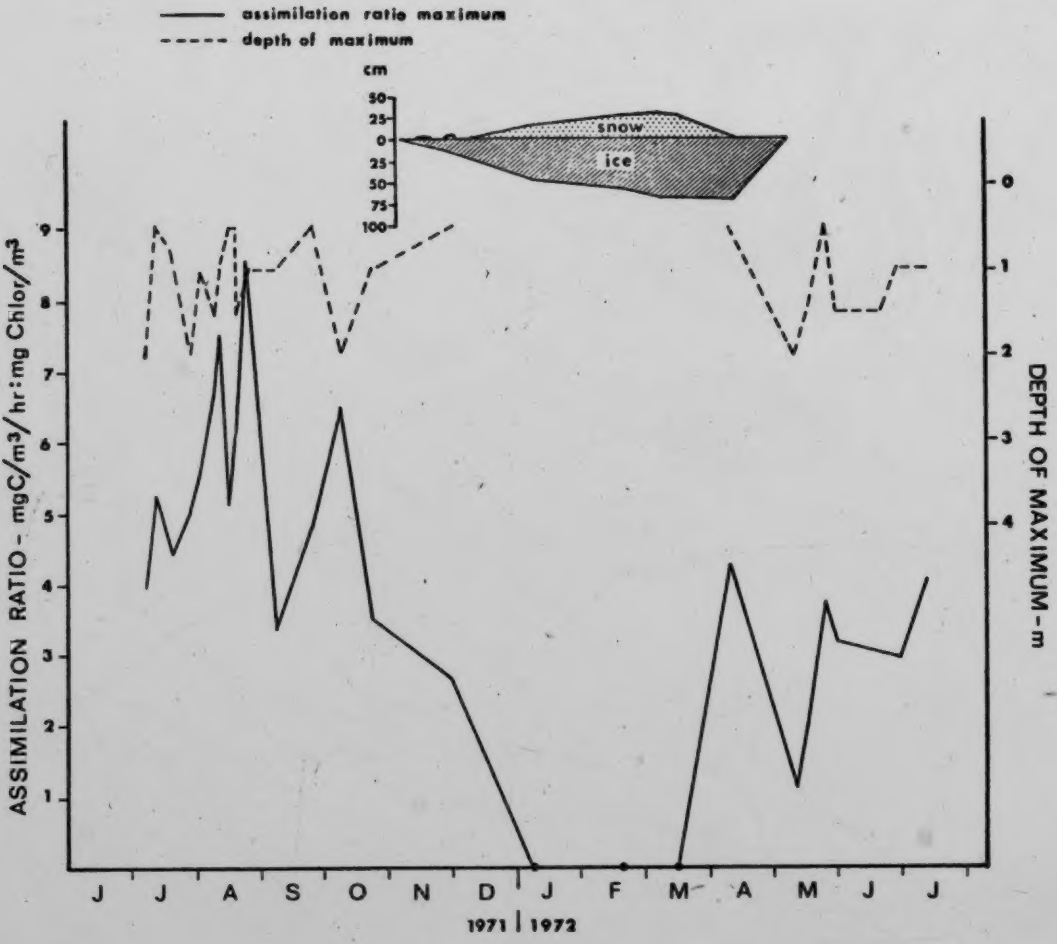


Figure 16. Maximum midday assimilation ratios, 1971-72, at main lake stations.

The highest ratios in this study occurred in August, 1971, a time when other phytoplankton parameters were also maximal. The highest ratio observed was 8.6 on August 25; August ratios averaged about 6.5. Assimilation ratios for the whole summer period of 1971 averaged about 5.5. Ratios declined in late October, November, and December, perhaps because of low light intensities or low temperatures at that time of year. The spring peak in April of 1972 did not produce the high ratios expected with optimal spring nutrient conditions. This may be because of less than optimal light conditions under spring ice, since ratios were much higher in ice free areas of comparable water temperature. Light was not limiting during the remainder of the 1972 sampling period, however, and the low ratios (about 2.4 to 3) during that time lead one to believe that there was a deficiency of nutrients then. Phytoplankton cell size may influence the assimilation ratios as well (Hickman, 1973) because small algae have a larger surface to volume ratio and may thus take up carbon at a faster rate per unit volume than larger cells. This may explain the peak in assimilation ratios in early October, 1971, because the phytoplankton at that time contained large numbers of ultraplankton.

Findenegg (1964) reported on types of phytoplankton production in lakes in the Eastern Alps of Europe. He designated three types of vertical productivity distribution curves corresponding to lakes of eutrophic, oligotrophic

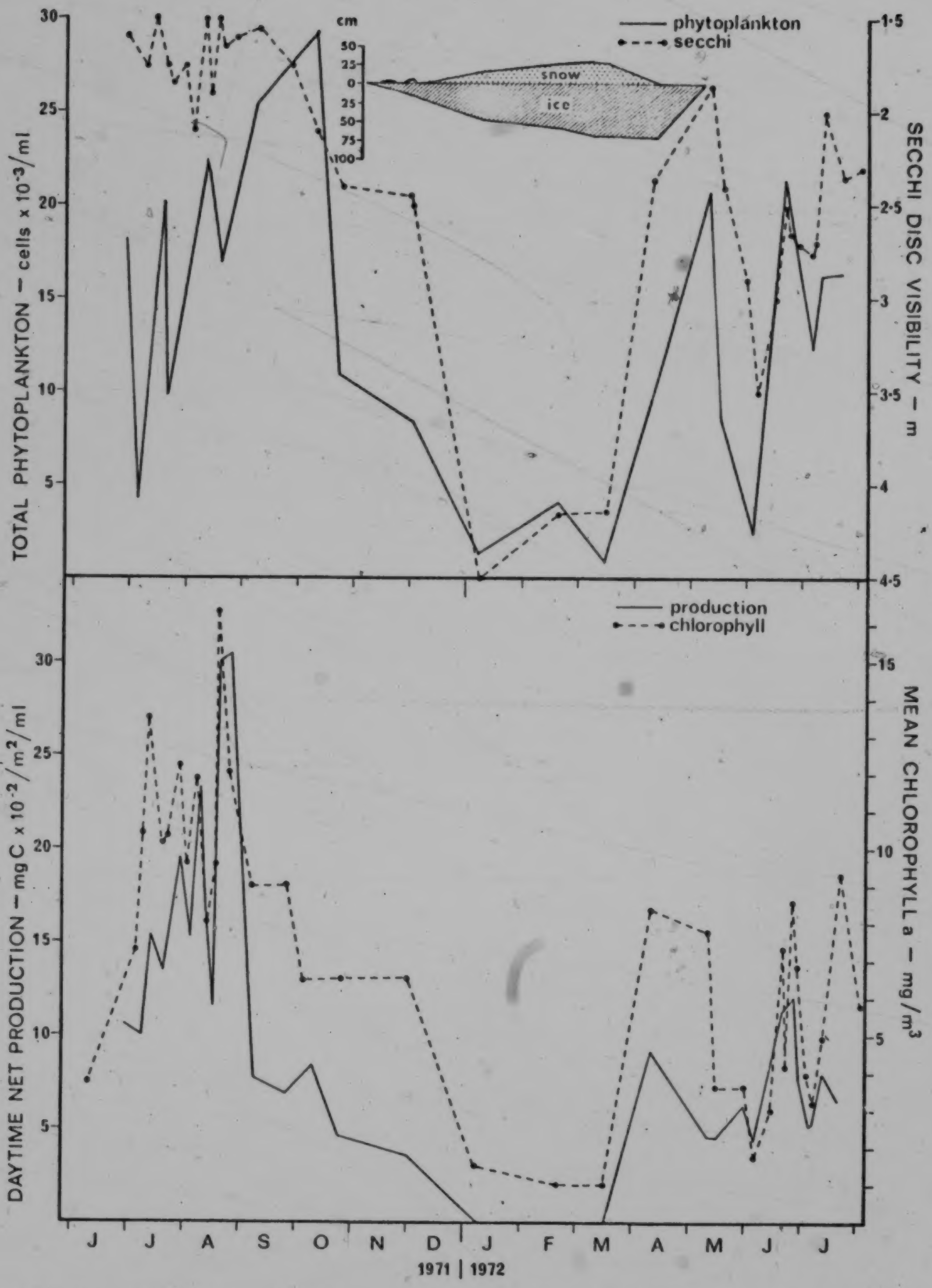


Figure 17. Phytoplankton production, mean chlorophyll a, cell numbers (at 1.0 m), and Secchi disc visibility, 1971-72, at main lake stations.

and incipient eutrophic status. The vertical productivity curves for Wabamun (Figure 11) mostly correspond to Findenegg's eutrophic type curve, with an important exception. The curves for the May-June period of 1972 are more similar to his curves which signify oligotrophy. They are characterised by slight surface productivity inhibition, a zone of optimal production which has a large vertical extent, and a relatively deep photic zone. As well, cell crops and chlorophyll concentrations are low, and light penetration into the water column is high (Figure 5). Findenegg suggests this curve type is a result of nutrient deficiency and is not light-limited except at the very surface by supra-optimal light. This may well apply to the curves in the May-June period in Wabamun, especially considering that the assimilation ratios discussed above also indicate nutrient deficiency at that time of the year.

This then, would indicate that phytoplankton populations and productivity, after a spring peak in what are probably nutrient-rich waters after winter, enter a period of greater nutrient limitation in May and June. No correlated nutrient fluctuations were evident in results of water chemical analysis examined for this study and in results of Klarer (1973), however, but this may be because of insensitivity of methods. If a nutrient deficiency exists, the question is what happens to the nutrients. Such deficiencies often arise in temperate lakes in the summer as a result of the sedimenting of nutrient-bearing seston into the hypolimnion where the nutrients are unavailable to the photic zone until fall overturn. Lake Wabamun does not develop a hypolimnion, however, and so this can not be the fate of these nutrients. A possible depository for these nutrients is suggested by data presented by Horkan (1971). He reported high standing crops of zooplankton (highest numbers of rotifers and crustaceans in the year) in the May-June period of 1970. It is conceivable then, that the spring phytoplankton outburst is cropped by zooplankton to the extent that the increased biomass of zooplankton ties up sufficient amounts of nutrients in May and June to limit phytoplankton populations. This would in turn inhibit further zooplankton growth, and as Horkan observed, zooplankton numbers declined through June and July, a process that may return nutrients to the water permitting increases in phytoplankton populations through July and August.

The phytoplankton productivity of Lake Wabamun is compared to productivity values for other lakes and ponds reported in the literature in Table 4. Wabamun seems to rank as a moderately eutrophic lake in terms of its productivity. It is interesting that Wabamun productivities are very similar to those reported by Hamilton (1963) for four lakes in south central Saskatchewan, an area of generally similar climate and geography to the Wabamun area.

TABLE 4

Phytoplankton Productivities From Selected Reports

Source	Description	Productivity mgC/m³/hr		mgC/m²/dy		gC/m²/yr
		max	mean	max	mean	
Anderson,	mountain lake					15.6
1970	Alta					
Anderson,	mt lakes,ponds	10				
1974	Alta-BC					
Donald,	temporary	400		5242		19.4
1971	ponds Alta					
Duthie and	reservoir	80		1650	1000	
Kirton, 1970	S Ont					
Fabris,	4 mt lakes, in				309	48.5
1966	order of				26	2.5
	increasing				84	6.9
	elevation Alta				60	5.5
Frey and	2 arctic lakes				50	7.8
Stahl, 1958	NWT				9	
Gelin,	eutrophic lake			3500		460
1971	gross prod					
	Sweden					
Hamilton,	4 prairie	99	87		1040	
1963	lakes gross	149	71		2570	
	prod	150	65		2720	
	S Sask	67	34		1890	
Rodhe,	eutrophic lake					104
1958	Sweden					
Schindler,	11 ELA lakes					24-81
1972	NW Ont					
	2 lakes					101
	S Ont					26
	L Winnipeg					9
Schindler	eutrophic lake					
and Comita,	gross prod-					500
1972	net prod 24hr-					250
	Minn					
Vollenweider	typical values					
1968	oligotrophic					<30
	eutrophic					>100
This study		116		3045	1515	170

Unless noted, annual production values are assumed to represent net daytime production

RESULTS AND DISCUSSION-THERMAL EFFECTS

A. Physical-Chemical

1. Temperature

The sampling stations in the warm water areas in this study (WO, SO) were chosen so as to be positioned well within the thermal plume where the water temperatures would be quite distinct from those of unaffected main lake stations, and the water column deep enough to allow vertical temperature stratification of the thermal plume. Station WO and SO had summer surface temperatures 3 to 7 C° warmer than main lake surface temperatures. At a depth of 1.5 meters, however, there was little difference in temperature between warm water and main lake stations. Summer surface temperatures in the Wabamun effluent were occasionally slightly above 30 °C. Winter surface temperatures in the ice free region around the Wabamun power plant effluent were about 14 to 17 °C near the mouth of the discharge canal but dropped rapidly with increasing distance from the canal mouth.

An area of water around both thermal discharges remains ice-free all winter. The size of this open area is in a sensitive balance with weather conditions; the coldest times during the winter coincide with the smallest ice-free areas. Warmer weather reduces the cooling rate of the thermal effluent, allowing it to melt back ice cover formed during colder periods. The thickness of ice cover surrounding the open areas increases with distance from the open area. Thus the extent of the ice-free area fluctuates during the winter, and is usually smallest during January. Allen (1973) presented a composite diagram illustrating the fluctuating size of the open areas at Wabamun and Sundance during the winter of 1970-71. Figure 18 presents this diagram as well as the delineation of a thermally affected area of the lake around the Wabamun plant. This latter area will be referred to later in a discussion of the effects of the thermal effluent on phytoplankton productivity.

As can be seen from Figure 18, the ice-free area enlarges dramatically towards the end of winter as air temperatures rise. There is a melting of the ice in the whole eastern end of the lake much sooner than in the western end, because the presence of the thermal effluents and ice free areas allows the warmer spring air and wind action to warm the open waters and hasten melting of the ice in that end of the lake. On May 2, 1972, it was possible to travel by boat from Kapasiwin Bay to Sundance along the eastern shore, while the western end of the lake was still ice covered. As mentioned by Klarer (1973), the lack of ice cover in the thermal plumes, a direct effect of temperature, is itself an important ecological factor.

The strict delineation of a definite area that is to be considered affected by thermal effluents is somewhat arbitrary, since thermal effects can be considered to extend to the whole lake if we are concerned with the process of

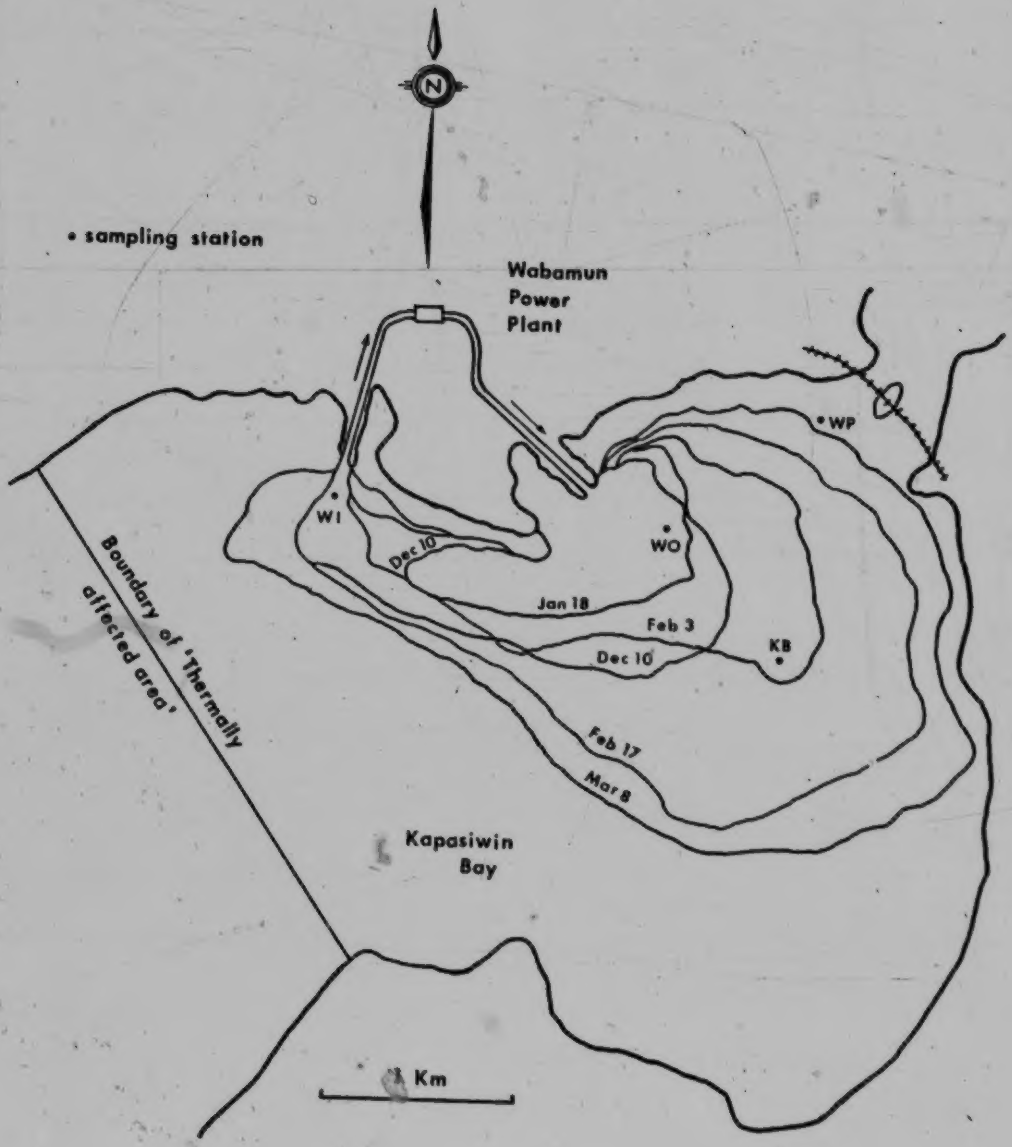

• sampling station
Wabamun Power Plant
WP
WI
WO
KB
Dec 10
Jan 18
Feb 3
Dec 10
Feb 17
Mar 8
Boundary of 'Thermally affected area'
Kapasiwin Bay
1 Km

Figure 18. Ice-free areas, Kapasawin Bay, winter, 1970-71 (from Allen, 1973), and 'thermally affected' area.

ice-melt, for example. Also, the bottom waters of Kapasiwin Bay are not warmed appreciably by the thermal discharges so that it may be desirable in some cases to delineate an affected volume of the lake. In general, at increasing distances and depths from the discharge canals, there is less effect of the thermal effluents. The arbitrary boundary depicted in Figure 18 was chosen in order to facilitate calculations of thermal effects on productivity in the lake. This will be discussed later.

2. Secchi disc visibility and light penetration

Figure 19 presents a graph of Secchi disc visibilities at main lake stations and in the two thermally affected regions, for times during the 1970-72 period when comparable measurements were taken. During the ice-free season of 1970, the Sundance power plant was not operating and Secchi disc visibility in the area of what was to be Sundance thermal discharge was very similar to the visibility in the main lake. Measurements during this same time period in the Wabamun heated zone indicated there was no obvious difference in turbidity between heated and unheated sites, although only six measurements were made. During 1971-72, there were higher turbidities in both thermal effluents than at stations in the main lake. When observations were made during this time, on only two occasions was turbidity equal in the effluent and main lake, and turbidity was never observed to be lower in heated areas than in the main lake.

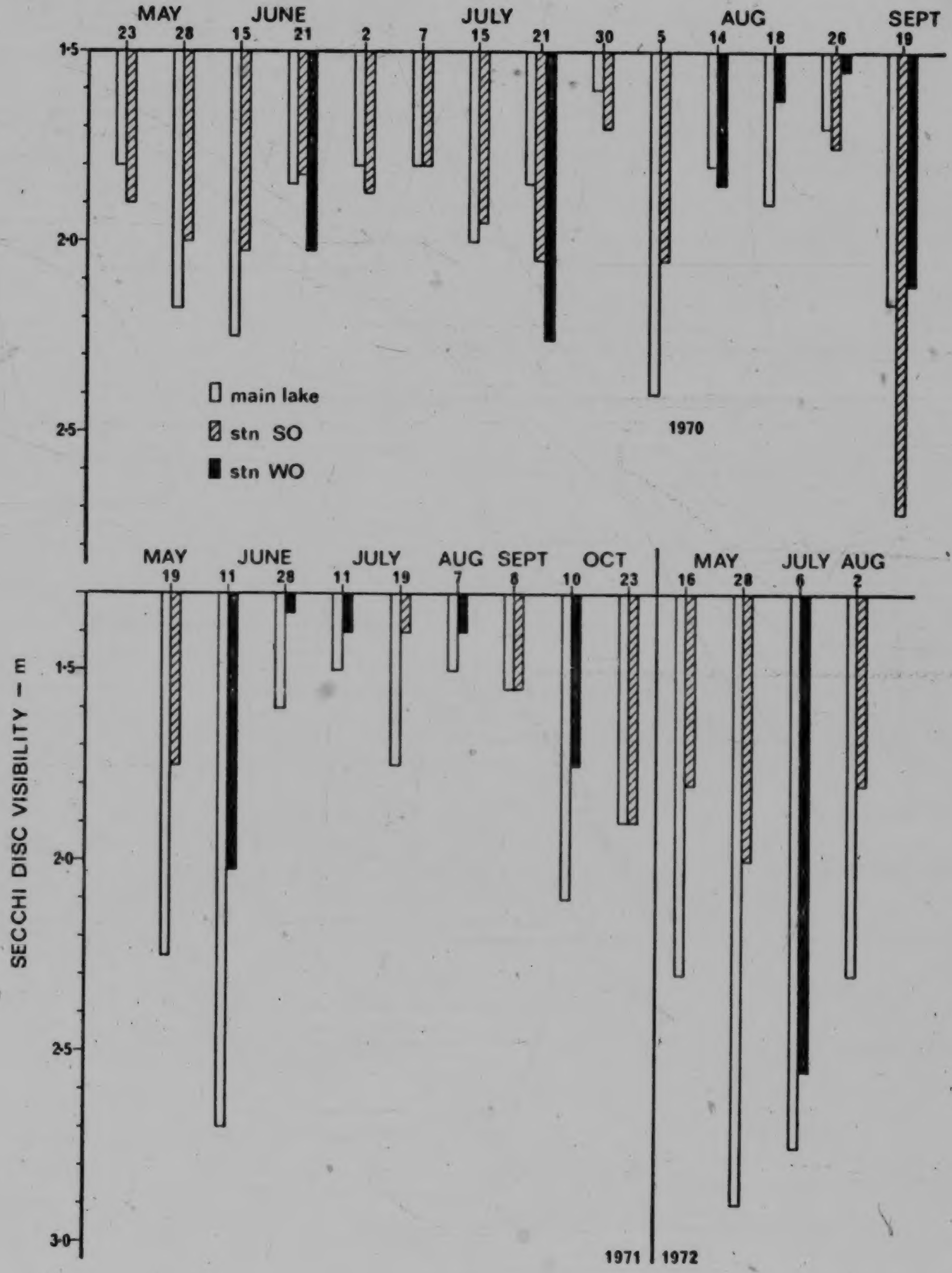


Figure 19. Secchi disc visibility, 1970-71, at main lake and effluent stations.

Horkan (1971) noted similar consistently higher turbidities (measured in Jackson Turbidity Units) in the heated area at Wabamun than in the main lake.

It is not immediately obvious what components of the seston are responsible for this increased turbidity. Turbulence in the discharge canals may be suspending inorganic particles, dead organic particles, benthic and epiphytic algae, or there may be higher phytoplankton populations in the effluents. The last possibility does not seem likely since turbidity at nearby station KB is lower than at WO, suggesting a portion of the seston settles out soon after the water leaves the canal. The question of differences in phytoplankton populations between heated and unheated areas will be discussed later. That increased turbidity is a result of the thermal discharges and is not natural to the effluent regions is suggested by the fact that turbidity at station SO was the same as turbidity at the main lake stations in the 1970 period when the Sundance power plant was not operating. Most likely, turbulence in the areas of thermal discharges is responsible for suspending at least temporarily, additional quantities of seston in the water.

Brezina _et al_. (1970) and Koss (1971) reported increased turbidities in thermal discharges as compared to unaffected lake areas in studies in Texas and North Carolina, repectively.

Increased turbidity in the water means an increase in the attenuation of light in the water, and it must be assumed that there is thus decreased light penetration into the water column at the two stations in the thermal effluent. Light measurements were taken in this study with the submarine photometer, but unfortunately, not enough comparisons between light penetration in heated and unheated areas were made to provide data that would bear on this assumption.

Wheelock (1969) noted that because of heavy macrophyte stands in the Wabamun heated zone in late summer, there was decreased light penetration. Macrophytes do have a noticeable shading effect in summer in both heated areas which likely decreases phytoplankton productivity, however, investigations in this study were designed to determine the effects of temperature on phytoplankton productivity. Incubations in the effluent areas were situated between or away from heavy macrophyte stands in order to avoid shading and thus have a more comparable illumination regime for simultaneous incubations in heated and unheated areas. Nevertheless, it must be stated that on the basis of Secchi disc visibility measurements, there is lower light penetration into the water column in heated than in unheated areas. The extent of these increased turbidities in the effluent areas is unknown, although turbidity decreases between stations WO and KB.

Winter snow and ice cover has been shown to decrease drastically the amount of light entering the water column

(Table 2). The effect of having no winter cover in a variable area surrounding the thermal discharges is obviously to allow unhindered penetration of light to the water surface all year round. Klarer (1973) noted that this was probably the most important effect of thermal pollution on epiphytic algae, as did Allen (1973) for aquatic macrophytes. It will be shown later in the report that the ice-free condition in winter is equally important for phytoplankton.

3. Water Chemistry

Lee and Veith (1971) in a discussion of possible thermal effects on water chemistry suggest that there should not be any changes in chemical parameters of lake water as a result of thermal pollution, other than changes in the percent saturation of oxygen.

Table 3 presents data on chemical parameters for several stations in Lake Wabamun. As noted by Hickman (1974), there seems to be no change in water chemistry in the thermal effluents. Only changes in the percentage oxygen saturation in the thermal effluent have been reported by others studying Lake Wabamun (Horkan, 1971; Klarer, 1973; Allen, 1973; Klarer, Hickman, and Gallup, 1973).

The only effect of operation of the thermal power plants on the dissolved solids of Lake Wabamun may be an increase of silica in the water as a result of fall-out of fly ash from the stack smoke of the two power plants (Gallup and Hickman, 1975).

B. Phytoplankton Populations

In the graphs in Figure 20, the total number of phytplankton cells at the three stations (main lake, WO, SO) is comparable in general but there were times when differences existed between stations. During the mid-August to mid-November period of 1971, surface populations of algae at station WO were noticeably lower than at the main lake station, station 19. This difference was not evident at a depth of one meter, however. Samples from station SO did not show any obvious differences in cell crops from main lake samples during either 1971 or 1972. Winter populations at the Wabamun open area stayed at generally higher levels than did populations under the ice at stations SC and AB. Main lake numbers declined to their low winter levels (found at both stations in February-March, 1972) in December but the open area populations did not so decline until January. Also, the spring peak in phytoplankton appeared slightly earlier at station WO than at the main lake stations.

There were no evident differences between station WO and 19 during the rest of the study, nor were there evident differences in the taxonomic composition of the phytoplankton between stations at any time during 1971-72. The cell numbers data for the five phytoplankton groups at the sampled times and stations is in Appendix 11.

Chlorophyll a values from the three stations (WO, SO,

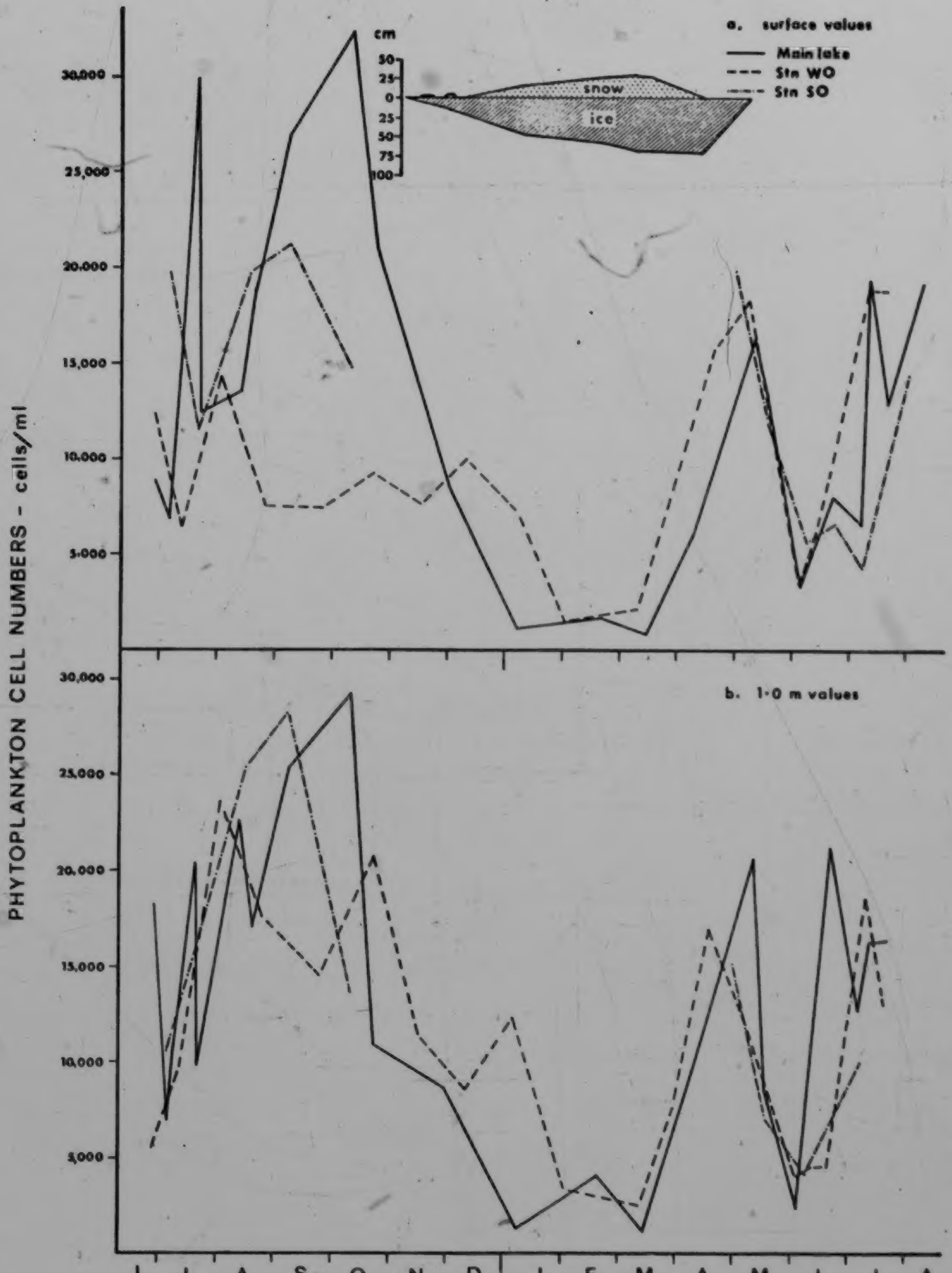


Figure 20. Phytoplankton cell numbers, 1971-72, at main lake and effluent stations.

19) tend to support the observation that phytoplankton populations differ between the three stations only at certain times (Figure 21 and 22). Mean chlorophyll concentrations (Figure 21) appear to have differed during mid-July to mid-September, 1971, when concentrations at station WO were lower than at station 19, and during winter when WO maintained fall concentrations farther into the winter and generally higher winter concentrations than did the main lake stations. Chlorophyll concentrations at the surface of the water column (Figure 22) were consistent with the results of surface phytoplankton cell numbers. Levels at station WO were lower than station 19 in the summer-fall sampling period of 1971, but higher in winter and in April, 1972. Stations SO and 19 did not differ noticeably. At a depth of one meter, the only difference noticeable between the three stations is the higher concentrations at WO than in the main lake during the winter.

In a further attempt to determine the similarity of phytoplankton populations at heated and unheated stations, the coefficient of community (Oosting, 1958) was calculated for several pairs of samples throughout the study period. This coefficient is a measure of the similarity of the two samples (a and b) to which it is applied. The formula for calculating the coefficient (as a percentage) is

$$\frac{\Sigma(2Wi) \text{ x } 100}{a+b}$$

where

a is the total cells/ml of sample a

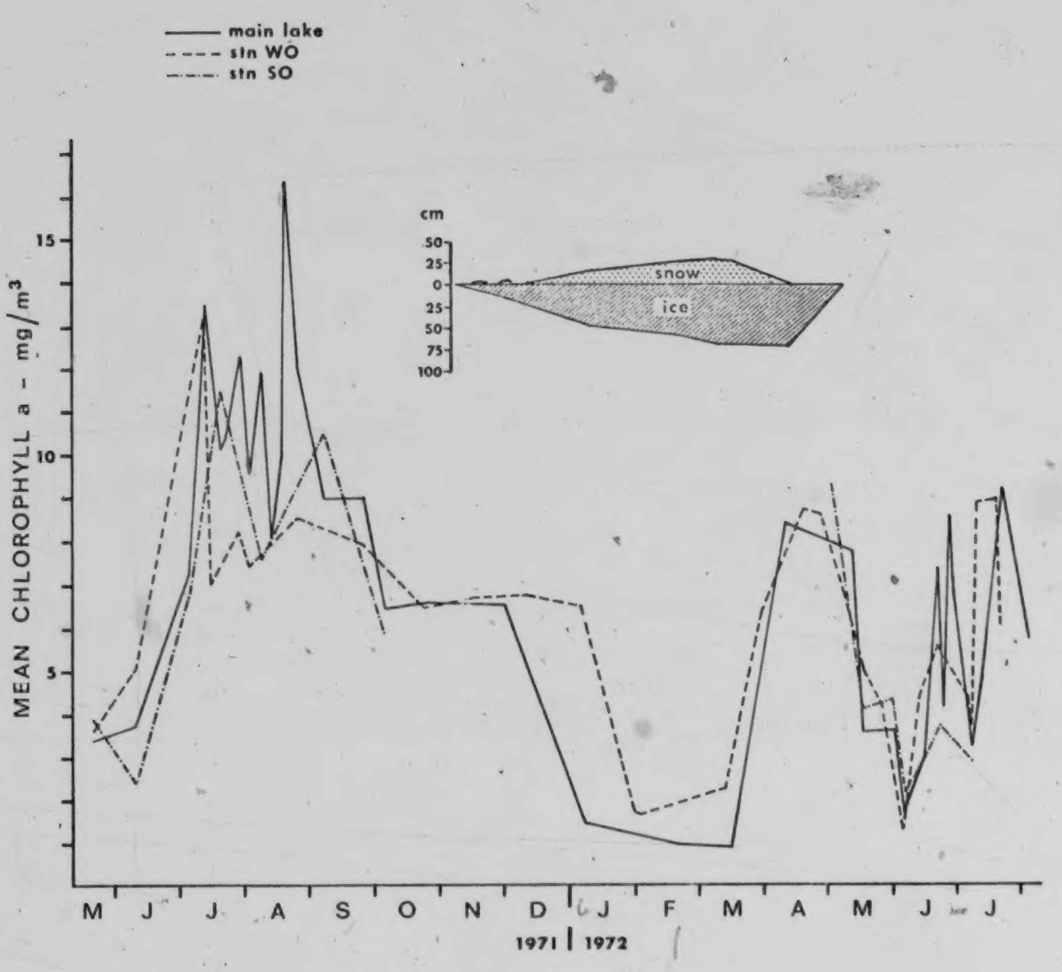


Figure 21. Mean chlorophyll a concentrations, 1971-72, at main lake and effluent stations.

b is the total cells/ml of sample b
Wi is the cells/ml of species i, from sample a or b, whichever has the lowest cells/ml of species i.

Identical samples will have a coefficient of 100%, and samples that have no two species in common will have a coefficient of 0%. The coefficient is a relative measure of similarity, in that all we can say of two samples with a certain coefficient is that they are more or less similar than two samples with a different coefficient. Wheelock (1969) and Lin (1968) have used this coefficient previously.

In this study, coefficients determined between main lake stations (19, 20, 21, 6) averaged 62% (n=10, range=45-73), between stations SO and 19 averaged 54% (n=16, range=31-96), between stations WO and KB averaged 73% (n=7, range=51-86), and between stations WO and WI averaged 64% (n=6, range=34-76). This seems to indicate merely that stations that are close together have phytoplankton communities that are more similar than stations that are farther apart. Thus the greatest dissimilarities here are between station 19 and the heated area stations. Greater differences were noted during the study, however, for example on June 22, 1972, the coefficient between stations 16 and SO was 19%, and between stations 16 and 19 was 26%. Station 16 is in the isolated portion of Goosequill Bay and could be expected therefore to have a distinct phytoplankton community.

It is difficult to know what effects on the phytoplankton community to expect as a result of the thermal

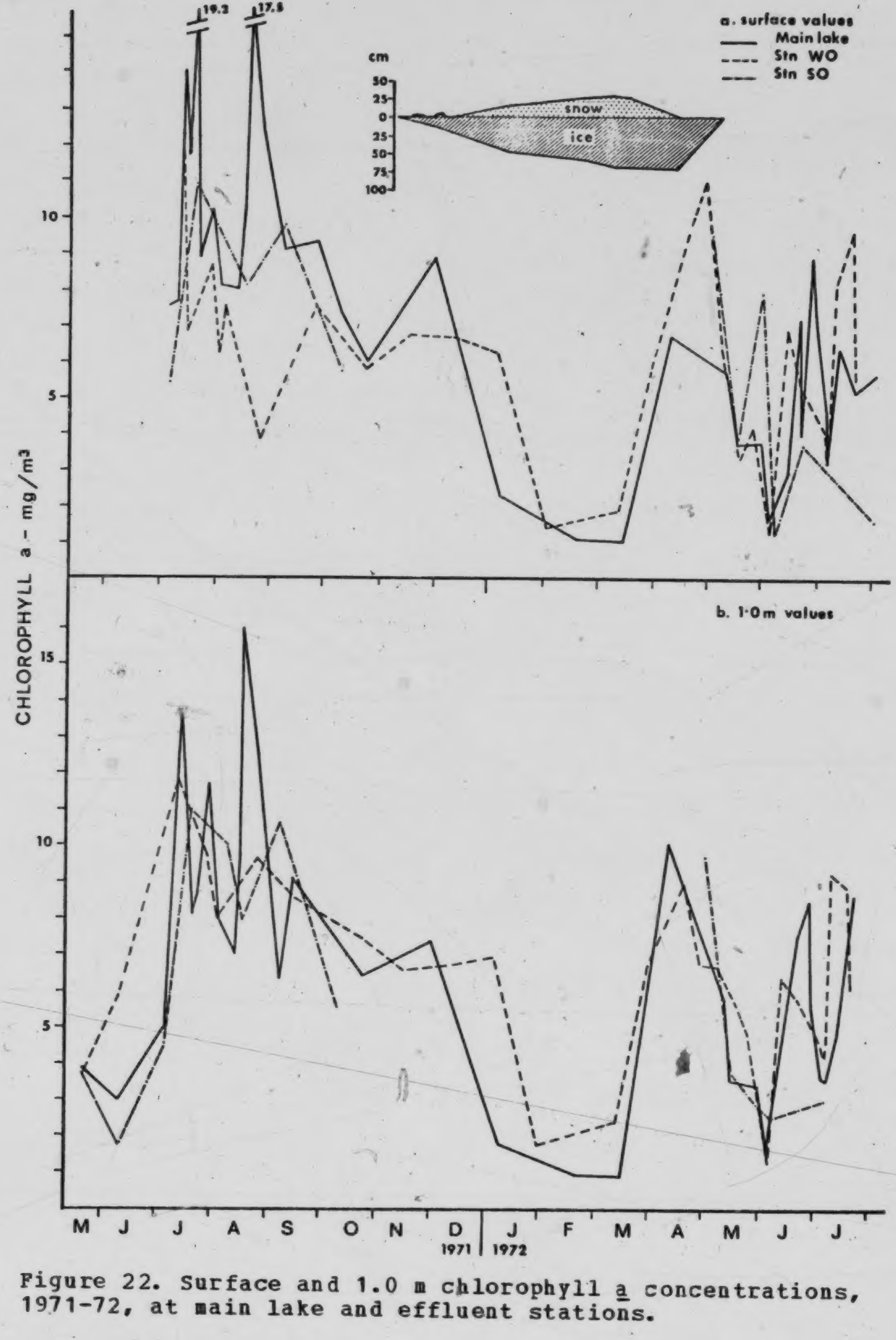


Figure 22. Surface and 1.0 m chlorophyll a concentrations, 1971-72, at main lake and effluent stations.

effluent from the Wabamun and Sundance power plants. Phytoplankton do not seem to be adversely affected just by passage through power plants, according to most of the literature on the subject. Several authors (Golueke, 1960; Patrick, 1969; Hirayama and Hirano, 1970; Levin et al., 1970; Lee and Veith, 1971; Williams et al., 1971) have found that temperature increments up to 10 C° and temperature levels up to 35 °C are not harmful to phytoplankton, or that thermal effluents do not significantly alter phytoplankton communities. On the other hand, it has also been observed that passage through a power plant can damage phytoplankton under thermal regimes more severe than the above temperatures (Williams et al., 1971), and that the phytoplankton community may change noticeably in thermally polluted reservoirs (Pidgaiko et al., 1972). Temperature increments during the winter in the thermal effluents at Lake Wabamun were 15 C° but as will be shown later, there was no depression of phytoplankton photosynthesis as a result.

Wheelock (1969) noted a 33% lower number of phytoplankton cells/ml in the heated area at Wabamun than in the unheated western end of the lake during the late summer of 1968. He suggested that competition between phytoplankton and macrophytes in the Wabamun effluent for light and nutrients resulted in lower phytoplankton populations. This is quite plausible because as macrophyte stands increase in biomass over the summer, they will effectively bind quantities of nutrients that will no longer be available for use by phytoplankton. The impact of this form of nutrient removal on the phytoplankton will depend on how much recirculation there is of Kapasiwin Bay water through the power plant and dense macrophyte beds. Frequent recirculation would allow more nutrient removal by the macrophytes from a specific water mass. Fitzgerald (1969) has noted such macrophyte nutrient removal which was detrimental to algae.

The lower phytoplankton numbers and chlorophyll a found at station WO in the late summer of 1971 occurred only near the surface, which complicates explanation of the phenomenon since we would expect macrophyte inhibition of phytoplankton to occur at all depths.

Nursall, Nuttall, and Fritz (1972) have estimated that as a general figure, 0.5% of the lake volume is circulated through the power plants each day. At that rate, there would be little chance for significant reduction in nutrient concentration by macrophytes unless recirculation of local water masses in Kapasiwin Bay was occurring. Aerial photographs published elsewhere (Nursall, Nuttall, and Fritz, 1972; Allen, 1973) indicate that there is often circulation of water between the Wabamun plant discharge and intake canals. Thus it seems possible that an area (or volume) of water in the Kapasiwin Bay region may become deficient in nutrients as compared to other areas of the lake and consequently phytoplankton populations may be depressed as well. However, as Wheelock noted, wind action has a mixing effect on the lake that would tend to homogenize plankton populations throughout the lake.

Lake currents in Goosequill Bay observed occasionally by the author have tended to move counter-clockwise in the bay, a pattern that would not favor recirculation of lake water through the Sundance power plant. Aerial photographs of ice cover (Klarer, Hickman and Gallup, 1973; Allen, 1973) also indicate little circulation of warmed water between the Sundance discharge and intake canals. The fact that there were no obvious differences between the phytoplankton communities of the main lake and station SO may be related to this type of circulation pattern.

In comparison with the May-July period of 1972, the late summer of 1971 had higher standing crops of macrophytes. Macrophytes had not grown to their peak standing crops by July of 1972. This factor may have contributed to the depression of phytoplankton crops in the Wabamun effluent in 1971 but not in 1972. Restriction of the 1971 depression to the surface waters is difficult to explain. It is possible that there is no depression of phytoplankton at station WO and that algal cells are merely settling out of the warmed surface waters which have reduced viscosity as a result of higher temperatures. Alternatively, recirculation of lake water may have been restricted to surface waters in the Kapasiwin Bay region.

Station WO maintained slightly higher phytoplankton populations during the winter than did the main lake stations. This also may have depended on recirculation of water through the Wabamun power plant, or circulation of water largely within the ice free region of Kapasiwin Bay, since if there were large movements of water in from the portion of the lake covered by snow and ice, then phytoplankton in the open area would not have been able to develop to their full extent in the better illuminated ice-free area. In fact, there probably were currents operating to remove water and phytoplankton from the ice-free area; a current has been noticed in the spring of several consecutive years running from the Wabamun plant intake canal region towards station SC and beyond. Such a current would tend to transport phytoplankton from the ice-free area towards station SC and may thus have minimized differences in the phytoplankton community between stations SC, AB, and WO.

It appears then, that the phytoplankton communities found in the effluent areas differ noticeably from the main lake communities only occasionally. Such occasions may be controlled by the degree of recirculation of effluent water back through the power plants (Coutant, 1970), in other words, the extent to which the phytoplankton becomes resident in the area of thermal discharge. This is an important point. Allen (1973) noted dramatic changes in macrophytes as a result of thermal discharges, as did Klarer (1973) in species of epiphytes. Horkan (1971) did not find such marked changes in planktonic rotifers as a result of thermal discharges, nor did Wheelock (1969) in the phytoplankton. Macrophytes and epiphytes are fixed in one spot and thus receive a more or less constant thermal regime depending on their location relative to the discharge canals. Plankton, however, is suspended in the water and is thus subject to lake currents. Plankters sampled in the thermal effluent are likely to be transients at that particular location because they will move with the water as it flows out from the canal, cools, and mixes into the lake.

Thus, the thermal regime of the plankton is uncertain and will depend in part on how often, or if, the thermal effluent water is recirculated back through the power plant. Infrequent recirculation may make it difficult to detect thermal effects on the plankton community as has apparently been the case so far at Lake Wabamun. A better understanding of lake currents would help clarify the situation. The point to be made is that plankters, in contrast to the littoral attached biota, are not necessarily resident in the thermal discharges.

C. Phytoplankton Productivity

Enclosing water samples in glass incubation bottles for use in phytoplankton productivity studies subjects the contained algae to the unnatural conditions of the bottle interior and fixes the algae to a specific depth and location during the incubation. The assumption is made that this treatment does not significantly affect the results obtained. Productivity incubations carried out in this study in the two thermal effluent areas required this assumption as well as one more. Water currents in the effluent regions carry entrained algae away from the discharge canals, at least near the surface of the water, and these algae undergo cooling at the same time as the effluent water cools down to ambient temperatures. By sampling phytoplankton and incubating them for four hours at a specific depth and location in the warmed areas, we are changing their thermal regime and spatial position from one of gradual cooling plus horizontal and/or vertical movement, to one of a relatively constant temperature and fixed location for four hours. It was therefore necessary to assume that the production rates calculated from incubations under these modified conditions represented the instantaneous rates of phytoplankton production at the particular point in time and space sampled.

1. Summer, 1970, comparisons

Figure 23 presents graphs of gross phytoplankton productivity (mgC/m³/hr) for several stations (SO, 5, SI, 3, 8, 19, 6, WO) at depths of 0, 0.5, 1.5, 2.0, and 2.5 m during the 1970 summer as measured with the oxygen productivity method.

Gross productivity at station SO during this period was certainly no greater than at other Sundance area stations

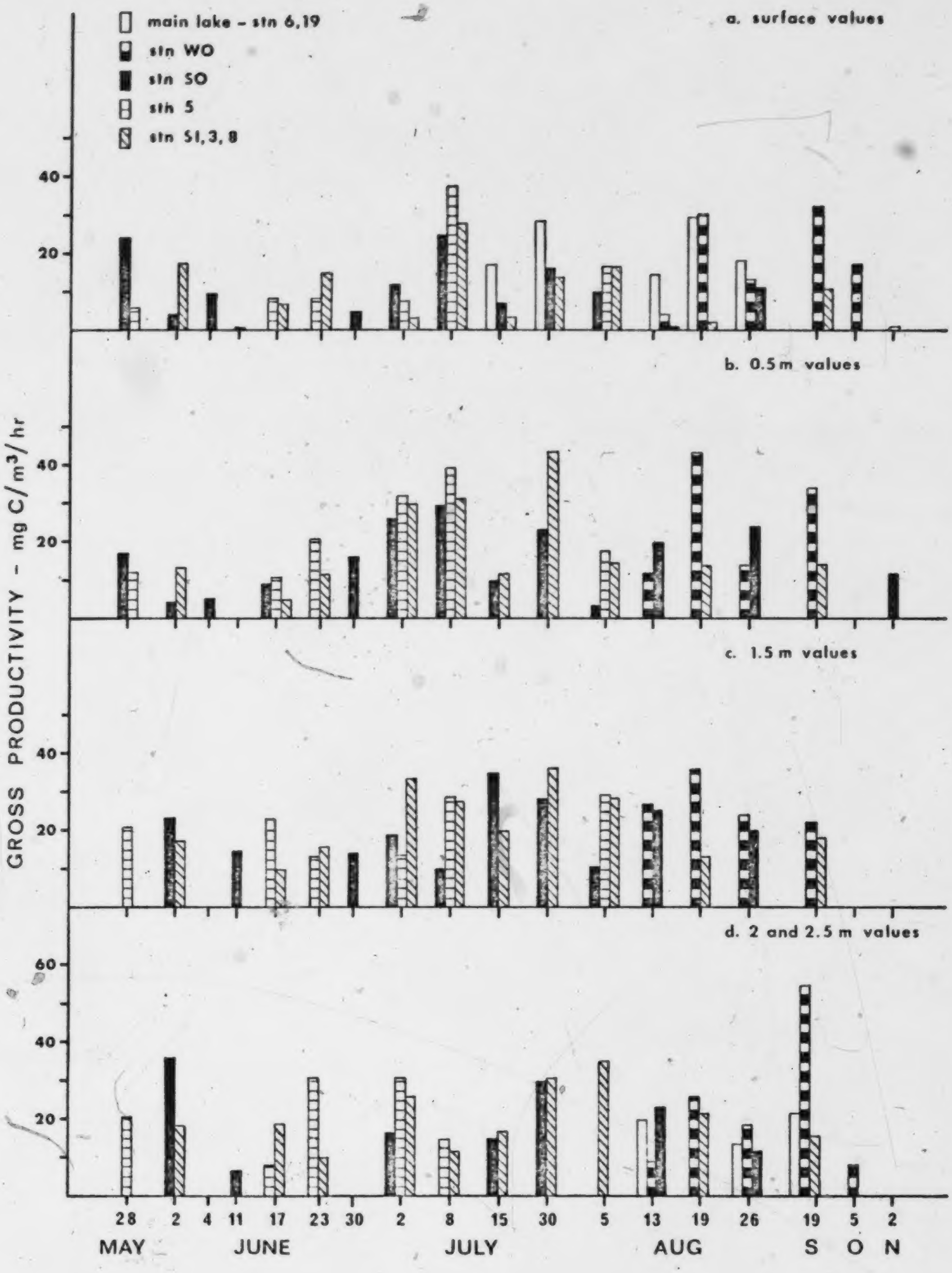


Figure 23. Midday gross productivity, 1970, at main lake, effluent, and near-shore stations.

(SI, 3, 8) and on the whole, was likely not any less than these three stations. Station 5 productivities, however, were sometimes higher than those of SO and occasionally greater than those of other Sundance area stations. Main lake stations (19 and 6) were not sampled as frequently or at as many depths as the former stations. It appears that surface productivity was greater in the main lake than at these previous stations, but there are not enough data to make comparisons at other depths. Station WO was sampled from mid August to early October. Productivity there was no lower than at the previously mentioned stations and may have been somewhat higher, however, infrequent samples make it difficult to detect trends at station WO.

In general, station SO had phytoplankton productivities that were no greater than productivities at other areas sampled, and were often actually less than those of certain other stations.

2. 1971-72 comparisons

A comparison of productivity (mgC/m^3/hr) at three stations (WO, SO, 19) for the depths of 0, 0.5, 1.0, and 2.0 m during the 1971-72 study period is presented in Figure 24 and 25. These graphs depict differences in production rates at various depths between the unheated station 19 and the two thermally affected stations, WO and SO.

Surface productivities during the summer of 1971 until early October at station WO were always slightly higher than

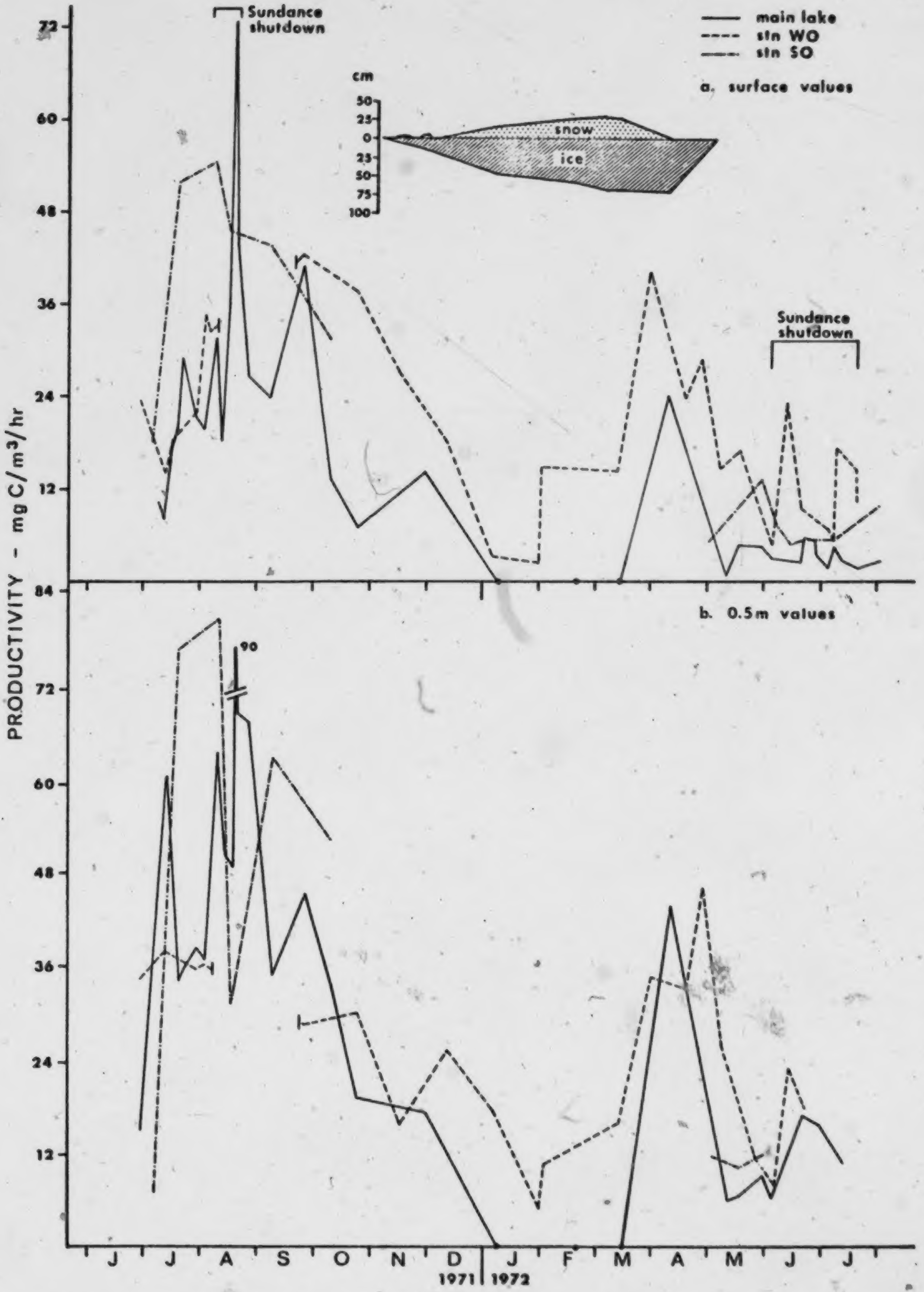


Figure 24. Midday net productivity, 1971-72, at main lake and effluent stations. Surface and 0.5 m values.

those of station 19 on the occasions when these stations were sampled simultaneously. Productivities at station SO, however, were markedly greater than at stations 19 during this period, except on one occasion during shutdown of the Sundance power plant. Measurements at station SO during Sundance shutdown in 1971 and 1972 indicated that surface production rates may have been inherently higher at this site than in the main lake, but rates at other depths were not noticeably different. Station WO had much higher surface productivities than station 19 during the remainder of 1971 and was active photosynthetically during the winter when there was no detectable photosynthesis in the main lake under ice and snow cover. Obviously, the ice-free condition at station WO allowed light penetration to occur in the water column at that time. During the rest of 1972, consistently and markedly greater productivity was recorded at station WO than at station 19. Sundance surface productivities were generally higher than main lake productivities in 1972 as well, except during the period of Sundance shutdown when they more closely approached, but remained somewhat greater than, productivities at station 19.

Surface production rates at all near-shore stations, whether heated or not, were consistently higher than at station 19 during the ice free season of 1972 (Figure 26). There was a tendency for this to occur at other depths as well, but not to as great an extent. There were no similar

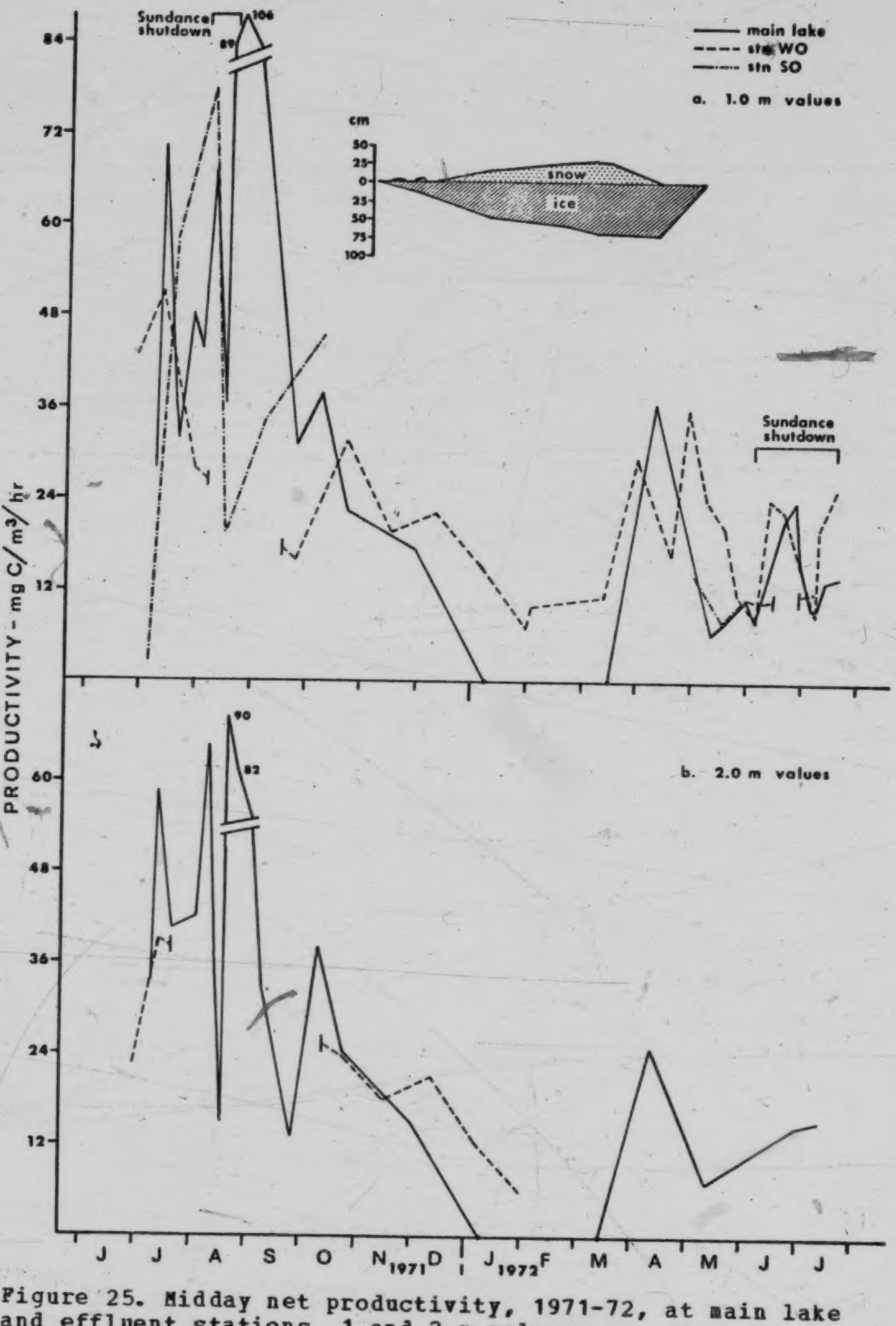


Figure 25. Midday net productivity, 1971-72, at main lake and effluent stations. 1 and 2 m values.

trends in chlorophyll differences between these stations. Slight differences in the nutrient regimes may have been responsible for this effect but it is unclear how that would affect surface productivities more than productivity at other depths. Differential amounts of light inhibition of photosynthesis may account for these surface discrepancies, in that phytoplankton at station 19 may be acclimatized to lower mean light levels than inshore phytoplankton because of the greater depth of station 19. Algae can be mixed through a deeper water column there, the mean light level of which is lower than at shallower sites.

Harris and Lott (1973) have suggested that the degree of light inhibition shown by phytoplankton is inversely linked to the light level to which the phytoplankton is acclimatized. They state that such adaption can occur within periods of less than a day. Thus, algae in near-shore regions may be adapted to higher light intensities in Lake Wabamun and thus may show higher surface productivity under conditions of strong light than algae in the main lake.

Production rates at 0.5 meter depths from late June until November 1971, were generally similar at station WO and station 19, although somewhat lower in the mid-July to mid-September period at station WO. Station SO appeared to have higher productivities than station 19 during this period, although the Sundance power plant was not operating on two of the six sampling dates. During the ice-free period of 1972, unfortunately, only three measurements were made at

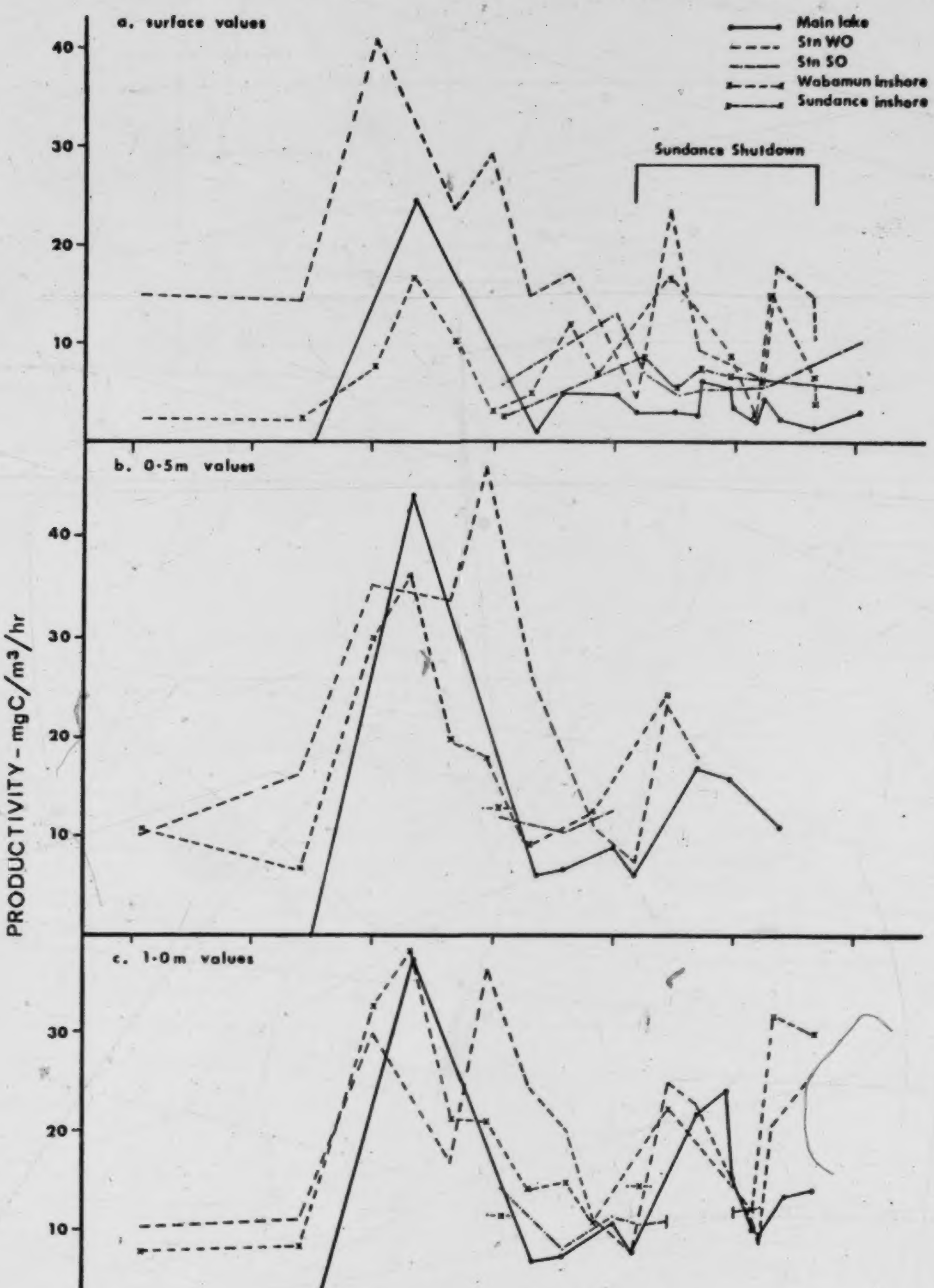


Figure 26. Midday net productivity, 1972, at main lake, effluent, and near-shore stations.

station SO at the one 0.5 meter depth. They showed higher productivities than station 19. Photosynthesis was constantly detectable through the winter at WO, when it was not at stations SC and AB. Productivities were generally higher at station WO than station 19 during the rest of 1972 until this depth was last sampled in late June.

Productivities at a depth of one meter show smaller overall differences between the three stations. Although only three simultaneous measurements were made in the July to September period of 1971, all three showed markedly lower productivities at station WO than 19. Overall differences between SO and 19 at this time were not obvious. Production continued through the winter at station WO but not at main lake stations under ice and snow. During the ice free season of 1972, productivity at WO was sometimes (late April to late May) higher than at 19 and sometimes (early June to early July) there was no difference. Station SO during 1972, on four occasions, showed productivities similar to station 19 whether the Sundance plant was operating or not.

Incubations were not done consistently at the two meter depth and the few data which are available only for stations WO and 19 do not show differences between the two until the onset of winter snow cover, when production ceased at main lake stations but continued at station WO.

Although productivity was not investigated at station SO during the winter period, it is assumed that phytoplankton photosynthes[illegible] continued in the ice-free region at Sundance much as it did in the Wabamun ice-free area.

Stations WI, WP, and KB in the Kapasiwin Bay region and stations 3, 8, and SI in the Sundance region were sampled from February 1972, to the end of the study to compare productivity at these inshore sites to productivity at the inshore heated areas. Surface productivity at station WO was always greater than productivity at surrounding stations on the dates when simultaneous measurements were taken (Figure 26). The difference was greater in the February to mid-May period than during mid-May to mid-July. At Sundance, productivities were higher at station SO than at surrounding stations when the Sundance plant was operating but SO productivities fell slightly below other Sundance stations during Sundance shutdown. This latter result compares with results of 1970 when the Sundance plant was not operating and surface productivities at station SO were not noticeably different from those stations (3 and SI)

At a depth of 0.5 meter, station WO again had generally greater productivities than surrounding inshore stations in the February to mid-May period but on two subsequent dates, had slightly lower production rates. Only station 3 in the Sundance area was sampled, and only once, at this particular depth.

Productivity at a depth of one meter was greater on seven of eleven comparisons at station WO than at surrounding inshore stations during the February to July period of 1972, although overall levels of productivity did not differ greatly between the two stations at this depth. In the Sundance region, samples were too infrequent to allow comparisons of station SO and other Sundance area stations at this depth.

The various inshore stations were not sampled for productivity at depths greater than one meter.

3. Intake-discharge comparisons

Direct comparisons of productivity between intake and discharge stations were made on five occasions at the Wabamun sites (WI and WO) and on three occasions at the Sundance sites (SI and SO), during the mid-June to early August period of 1972 (Table 5). It was hoped that simultaneous sampling of intake and discharge sites would provide a more direct comparison of productivity before and after heating since presumably phytoplankton at the discharge sites would have been circulated through the power plants after having been withdrawn from the intake sites, and thus phytoplankton populations would be quite similar at the two sites. This was not always the case, however, as evidenced by the chlorophyll a values in Table 5.

Surface productivities were increased in the thermal effluent on four out of five dates in the Wabamun area, but the assimilation ratio (productivity/chlorophyll) was only increased on three of the five dates. Only one measurement was made at 0.5 meter depth. Productivity at one meter depths decreased three times out of four in the effluent but the assimilation ratio decreased only twice.

TABLE 5

Phytoplankton Parameters
Discharge and Intake Sites-1972

Date	Stn	Z (m)	Production mgC/m^3/hr		Chlor. a mg/m^3		Assim. Ratios		Temp. °C	
			Dis	Int	Dis	Int	Dis	Int	Dis	Int
13/6	WO and WI	0	23.53	16.91	6.7	3.2	3.38	5.30	21.3	15.3
		0.5	23.14	24.50	3.2	3.2	7.21	7.64	21.0	15.3
		1.0	24.47	22.24	6.2	7.2	3.81	3.10	16.6	15.3
5/7	"	0	7.16	2.64	4.1	1.8	0.15	1.44	24.9	19.5
		1.0	10.53	12.18	4.6	3.7	2.30	3.32	19.2	19.2
10/7	"	0	17.92	25.50	8.2	12.6	2.19	2.02	20.2	17.0
		1.0	20.52	31.56	9.3	13.1	2.21	2.41	19.8	17.0
19/7	"	0	14.88	8.22	9.6	11.1	1.55	0.74	24.3	18.0
		1.0	25.62	29.96	8.9	15.1	2.90	1.98	18.8	17.9
20/7	"	0	10.68	4.41	6.1	7.4	1.76	0.60	27.5	18.5
15/6	SO and SI	0	4.99	5.48	3.0	6.8	1.68	0.81	17.3	16.5
22/6	"	0	5.53	7.74	3.7	4.4	1.50	1.77	17.0	17.1
2/8	"	0	10.23	5.35	1.5	7.1	6.69	0.75	24.6	18.7

At Sundance, only surface productivities were compared between stations SI and SO. On the first two dates however, the Sundance plant was not operating, and production was higher at station SI but the assimilation ratios varied. Both productivity and productivity per unit chlorophyll increased in the effluent when the plant was operating.

These results are not as clear cut as was hoped for.

However, they indicate that passage of phytoplankton through the power plant with a consequent rise in water temperature had, in general, a stimulatory effect on phytoplankton photosynthesis.

4. Previous statement

Comparisons of the productivities of heated and unheated areas have been reported earlier (Noton, 1973). Differences reported then were determined as to their statistical significance using paired and unpaired t-tests (Sokal and Rohlf, 1969). The tentative conclusions reached then on a statistical basis, and the statements above made from inspection of graphs and values, are largely in agreement. Some slight differences noted in this report had not been found statistically significant in the earlier report. It is doubtful, however, if use of the t-test in the former situation was valid, because the groups of values compared may not have had normal distributions, a requirement for use of t-tables. Sample sizes were too small to allow determination of statistical distributions.

Productivity values reported earlier (Noton, 1973) were calculated using the filtration error correction factor (1.65). As was mentioned in the discussion of methods, this factor was not used here.

5. Productivity-temperature relationships

In Figures 27-29, a comparison of phytoplankton

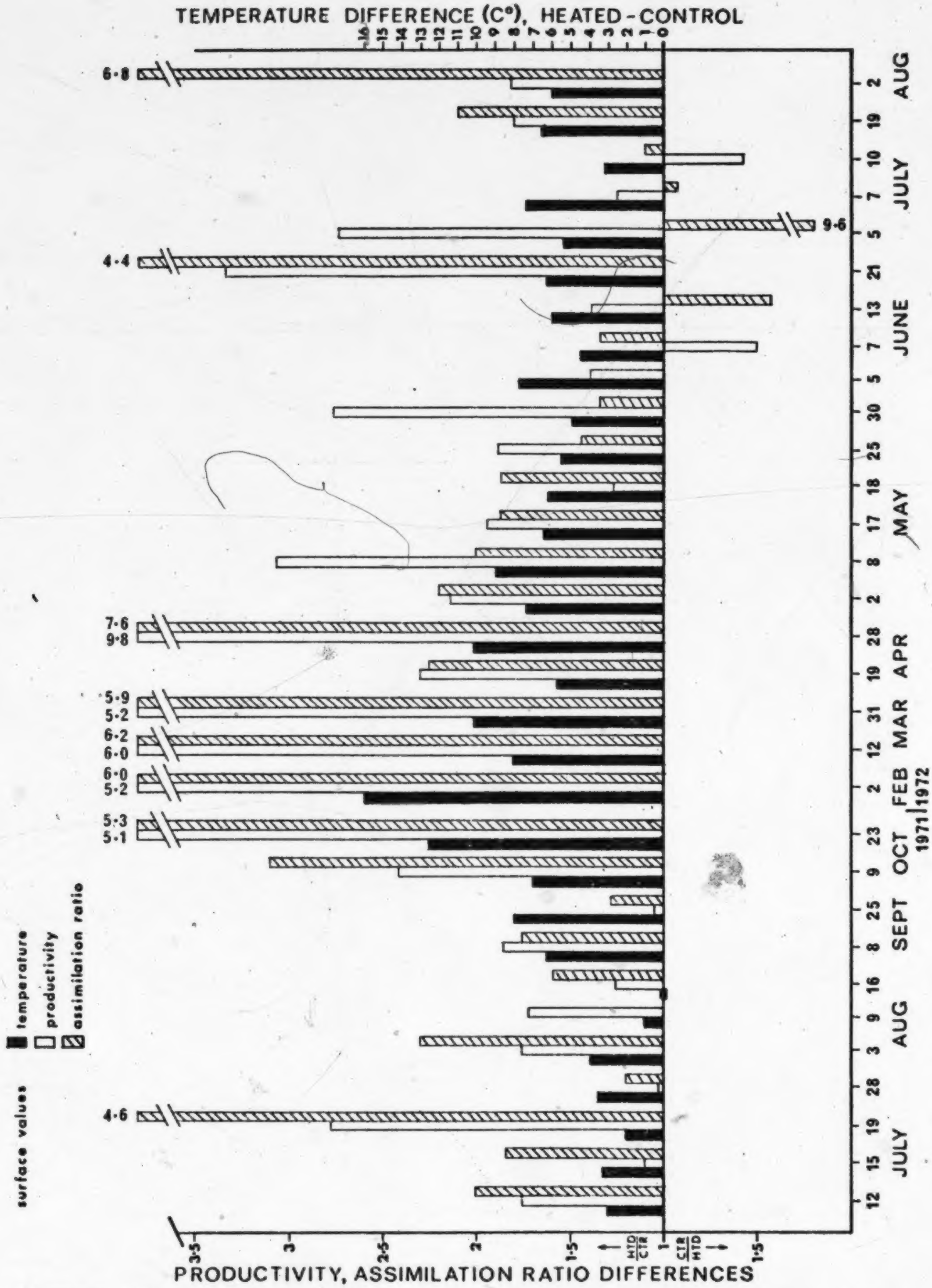


Figure 27. Differences in productivity, assimilation ratio, and temperature, 1971-72, between heated and unheated stations. Surface values.

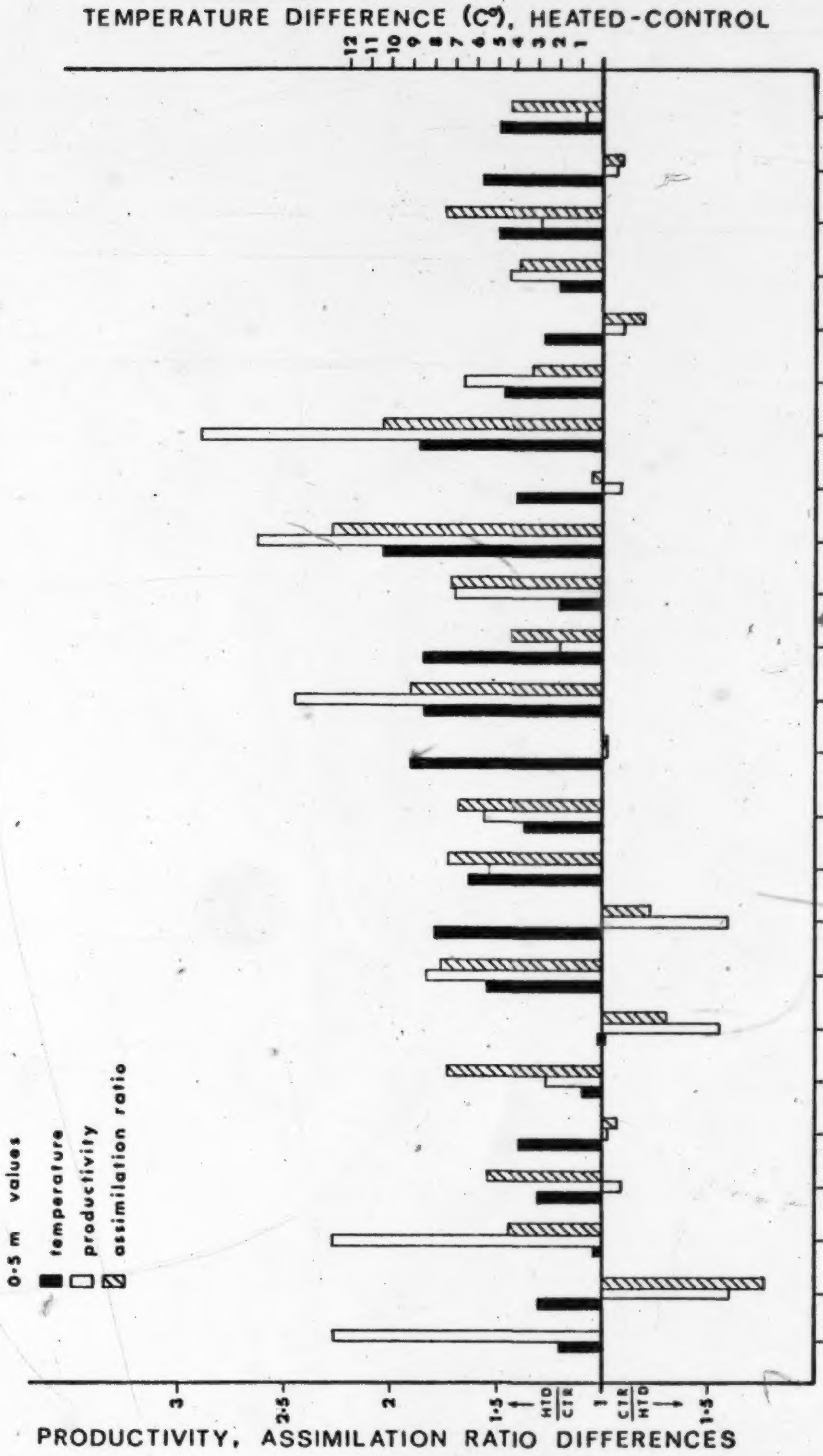


Figure 28. Differences in productivity, assimilation ratio, and temperature, 1971-72, between heated and unheated stations. 0.5 m values.

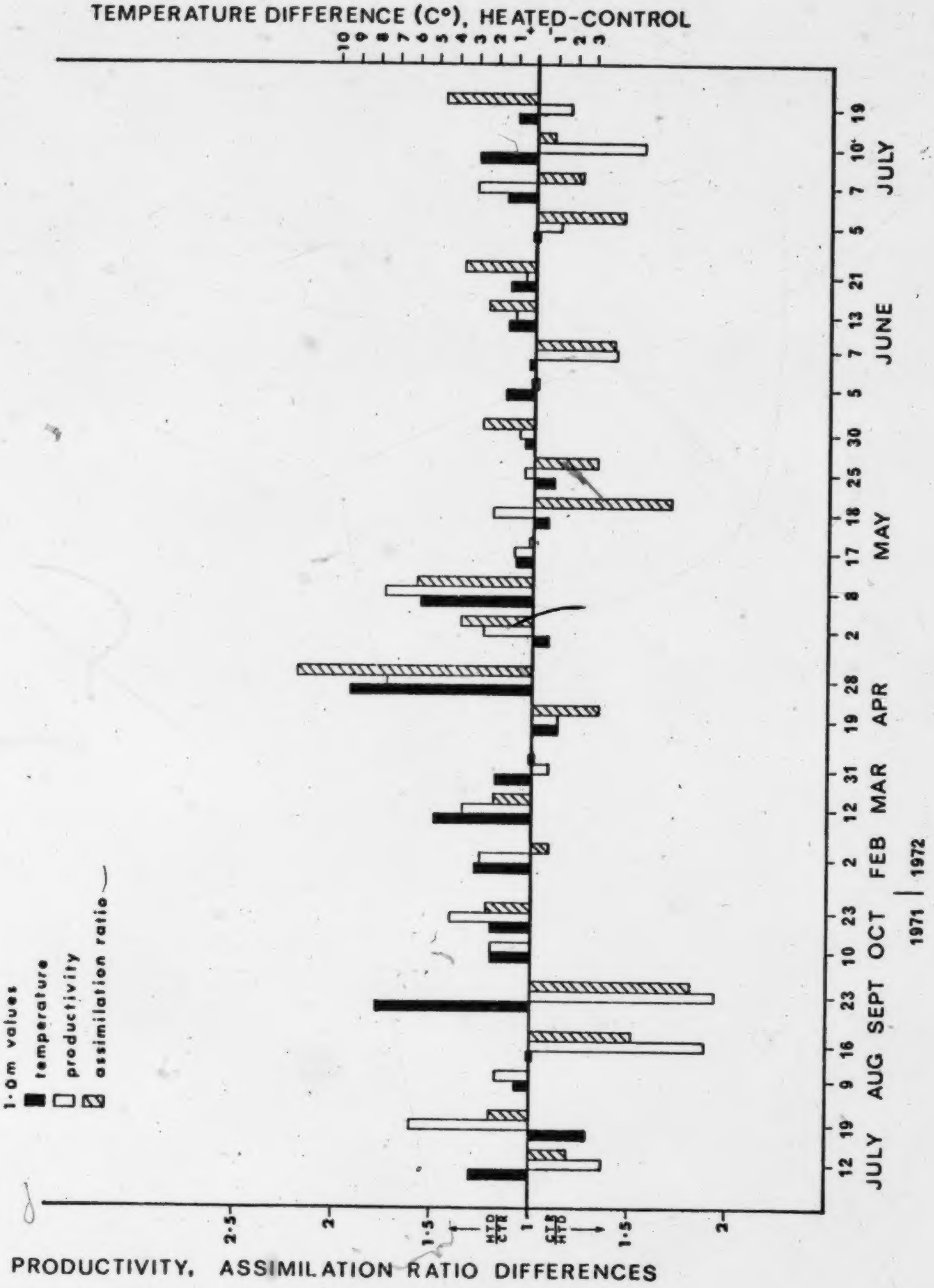


Figure 29. Differences in productivity, assimilation ratio, and temperature, 1971-72, between heated and unheated stations. 1.0 m values.

productivity, productivity per unit chlorophyll (assimilation ratio), and temperature, at heated and unheated stations, is presented. Plotted are values from the depths of 0, 0.5, and 1.0 meters, for the 1971-72 study period. These comparisons are taken only from the results of productivity incubations that were done simultaneously in heated and unheated areas and thus illustrate more directly the effects of the thermal effluent on phytoplankton productivity than do the graphs of Figures 24-26. Productivity and assimilation ratio results (Figures 27-29) are presented as a ratio of the value at the heated site to the value at the control site (Xw/Xc) when heated values were higher, or of the inverse (Xc/Xw) when control values were higher. Temperature is expressed as the difference, in centigrade degrees, between heated and control sites; a positive value indicates higher temperatures at an effluent station.

The three graphs illustrate the surface nature of the thermal effluent, as temperature differences are greatest at the surface of the water column, but less so as depth increases.

Both productivity and productivity per unit chlorophyll are greater in the thermal effluents than at unheated sites. These graphs support the observations made from Figures 24-26. Productivity is thus stimulated in the thermal effluents in that there is greater photosynthesis per unit chlorophyll there, as opposed to simply a greater absolute amount of photosynthesis. The latter may have been a result of a higher phytoplankton population, but the assimilation ratios show that photosynthesis itself is stimulated.

The stimulation of phytoplankton primary productivity is greatest at the surface of the thermal effluent and during the October to early May period. This period corresponds to the time of low ambient water temperatures, high temperature increments in the power plant steam condensers, low pumping rates of cooling water, and ice cover of the main lake. There appears to be a general correlation between differences in temperature at compared stations and differences in productivity and assimilation ratios, in that both increase in winter but decrease with depth. This will be discussed later. Changes in productivity and in assimilation ratios appear closely related, as would be expected, because the assimilation ratio is a partial function of productivity.

The relationship between productivity and temperature at heated and control sites is plotted in Figure 30. The ordinate is the log of the ratio of productivity at an effluent station and productivity at a control station; the abscissa is the temperature difference between the two. Each point on the graph represents the results of a pair of simultaneous incubations at an effluent and control station, at a specific depth; thus if incubations were conducted simultaneously at depths of 0, 0.5, and 1.0 m at both stations WO and 19, three points would be plotted on this

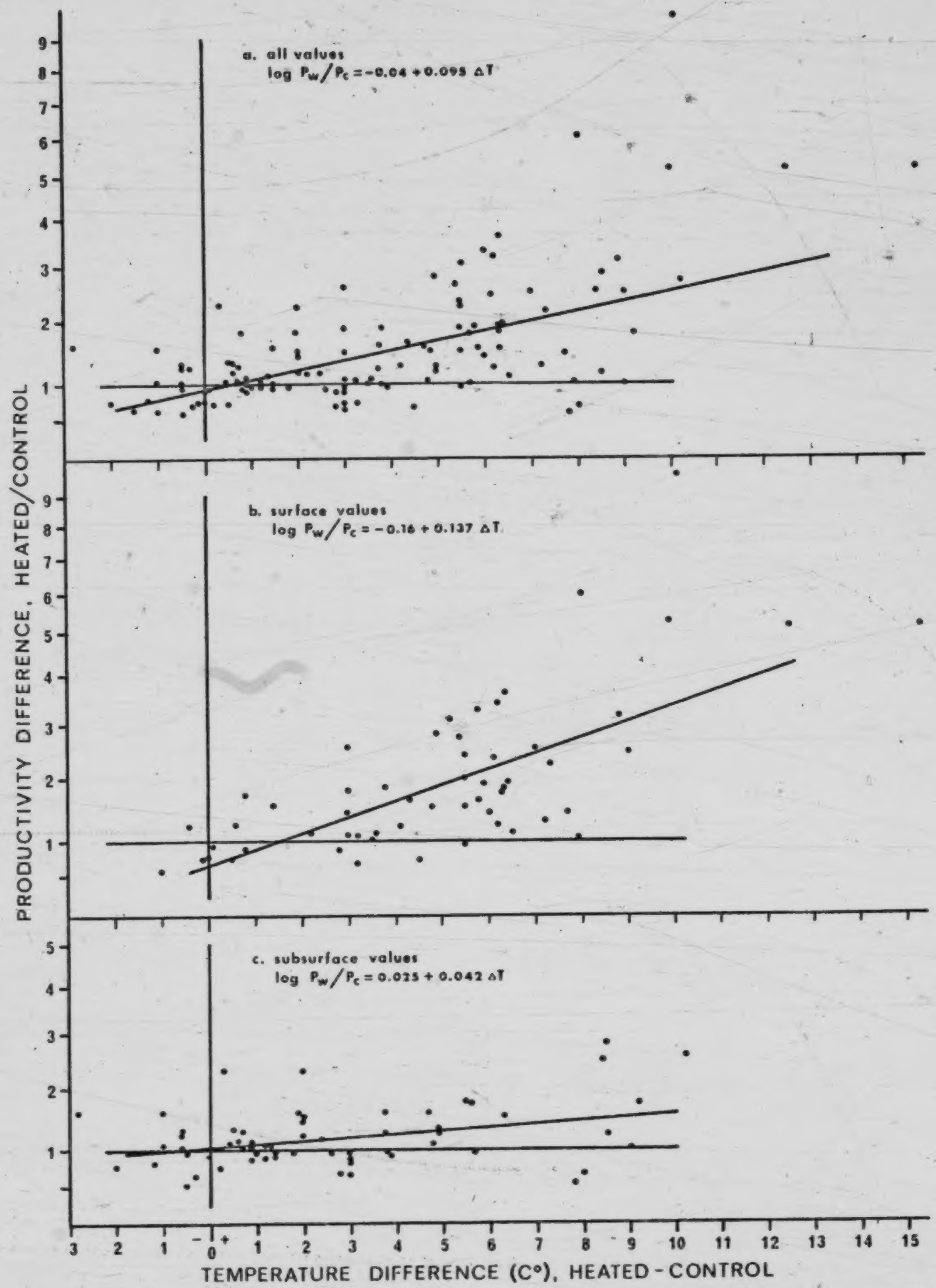


Figure 30. Productivity differences (Pw/Pc) versus temperature differences (C°), 1971-72, for heated and control stations.

graph.

Figure 30-a presents all such points. There is a significant positive correlation ($r=0.59$, $n=117$, $p<0.01$) between differences in productivity and differences in temperature between compared stations. From the graph, an increase in temperature of ten centigrade degrees increases productivity by a factor of approximately 2.6 (the Q_{10} value). Considering results of comparisons at the surface of the water only (Figure 30-b), there is a closer correlation ($r=0.72$, $n=57$, $p<0.01$) between changes in temperature and productivity, and the Q_{10} value is 3.8. There was not a significant correlation between temperature changes and productivity changes at depths of 0.5 meters or one and two meters, when considered by themselves. When all subsurface values are considered together (Figure 30-c), there is a weak correlation ($r=0.33$, $n=61$, $p<0.01$) between changes in temperature and productivity. The slope of the regression line for subsurface values is not significantly different from zero, however.

Regression lines drawn to fit the relationships in Figure 30 cut the ordinate for the most part at values less than unity. This indicates that for incubations at effluent and control sites when there was no temperature difference, productivity was lower at effluent sites. This may be because of increased turbidity and consequent lower light levels at effluent stations (turbidity has been discussed previously) which may thus partially counteract thermal stimulation of productivity. More evidence for turbidity limitation of photosynthesis at effluent stations is given by the fact that stimulation of subsurface productivity and assimilation ratios is not as great per unit temperature increase as it is at the surface of the water column. Light levels at the water surface would not be affected as much by these increased turbidities as light levels at greater depths. The lateral extent of this effect is not known, but elevated temperatures often extend past station KB, while elevated turbidities apparently do not reach station KB.

In the graphs of surface production, assimilation ratios, and temperature changes (Figure 27), the period of greatest percent stimulation of productivities was during the October to April period. Stimulation of productivity by thermal pollution when ambient temperatures are low is a common finding according to the literature on the subject, as will be discussed later. This fits well with the October to April results here. The values of heated-control comparisons in Figure 30 were inspected to see if the degree of stimulation of productivity could be related to temperatures at control sites. No such trends could be detected from these graphs. However, it seems such a relationship should exist, and might be detectable with larger sample sizes.

The stimulation of photosynthesis by thermal effluents may be by a combination of directly speeding up algal metabolism with elevated temperatures and effecting a faster rate of supply of nutrients to the cells. Increased rates of diffusion of dissolved molecules in the water can be expected with higher temperatures (Lee and Veith, 1971; Levin et al., 1971) and increased turbulence associated with a thermal discharge may also make nutrients more available to algal cells. Turbulence is important in controlling the rate of supply of nutrients to phytoplankton (Verduin, 1969; Munk and Riley, 1952).

6. Other reports

Several other studies have dealt with the effects of thermal pollution on phytoplankton productivity. Pidgaiko et al. (1972), working on a thermally polluted reservoir in the U.S.S.R., found higher productivity in heated areas, but also found higher biomasses such that the productivity to biomass ratio (P/B) was no greater in heated areas. This contrasts with the finding of higher productivity per unit chlorophyll in this study.

Brook and Baker (1972) in a study of chlorination effects at power plants, found a slight inhibition of phytoplankton photosynthesis and a 50% increase in phytoplankton respiration when samples with an ambient temperature of 23-25 °C were incubated at 32-36 °C with no chlorination. Both these temperature ranges are above those encountered in Lake Wabamun, where no such inhibition of photosynthesis was found.

Hamilton et al. (1970), also studying chlorination effects at thermal power plants, found that raising the temperature of phytoplankton samples from intake areas by 6-7 C° always increased productivity when the ambient water temperatures were less than 23.5 °C. This is the maximum ambient water temperature recorded at Lake Wabamun in this study.

Morgan and Stross (1969) studied the effects of passage through a power plant cooling system on phytoplankton. The plant was on the Patuxent River Estuary, the same plant studied by Hamilton _et al_. (1970). It was found that with temperature increments of 6-9 C°, and ambient temperatures up to 16 °C, plant passage had a stimulatory effect on phytoplankton productivity. With ambient temperatures above 23 °C, productivity was inhibited.

Carpenter, Peck, and Anderson (1972) also studied chlorination effects on entrained phytoplankton. With no chlorination and ambient water temperatures up to 18 °C in a marine environment, there was no residual effect of plant passage on phytoplankton productivities measured at ambient temperatures.

Tilly (1973-seen only in abstract), investigating heated and unheated areas in a reservoir used for cooling power plant thermal effluents, found surface rates of productivity higher at a heated site, but at greater depths, productivity was not so stimulated. Seston content was greater in the heated zone. This seems very similar to the situation at Lake Wabamun. Respiration was higher in heated areas according to Tilly, but respiration per unit area was lower.

Williams et al. (1971) found strong depressions of phytoplankton photosynthesis, that were not reversible within 24 hours, in a study of thermal effects on marine phytoplankton at a power plant on Long Island Sound. Ambient temperatures were about 23 °C and discharge temperatures were about 38 °C. The latter is considerably higher than temperatures encountered in this study.

Patalas (1970) reported that gross primary productivity of phytoplankton in a lake heated by a thermal effluent (mean summer epilimnion temperature of 26-28.5 °C) was double that of an unheated lake (mean summer epilimnion temperature of 21-22 °C). It is unclear whether these were two separate lakes or two basins of the same lake.

Koss (1971) found negligible effects of passage through a power plant alone on phytoplankton productivity, but with an increase in temperature by itself, productivity of phytoplankton from intake areas was stimulated. Also, stimulation was greater with lower ambient temperatures and higher temperature increments. This is similar to the large increases in surface productivity noted in Lake Wabamun during winter months. Koss' study was done on a lake in North Carolina but intake temperatures apparently did not rise much above 20 °C because water from the hypolimnion was used for cooling purposes. Temperature increments were about 9 C°.

Warinner and Brehmer (1966) found a pattern similar to many studies of thermal effects on phytoplankton photosynthesis in that productivity of marine phytoplankton was stimulated during the winter but depressed during the summer. They studied only the effects of increased temperatures, not effects of plant passage, but found that above ambient temperatures of 15 °C, productivity was depressed. Temperature increments were around 5 C°. No such depression of productivity was found in this study at similar ambient temperatures.

No deleterious effects on, and a possible stimulation of, phytoplankton photosynthesis by plant passage alone, were found by Gurtz and Weiss (1972). Temperature increments associated with plant passage were always found to be inhibitory to photosynthesis at all ambient temperatures involved. They investigated temperature increments of 5.6, 11.1, and 16.7 C° and ambient temperatures of 8.4 to 28.3 °C, at Lake Wylie, North Carolina. At higher ambient temperatures and greater temperature increments, there was a tendency for greater depression of photosynthesis. This is in contrast to results of this study where no depression of photosynthesis was recorded.

In summary of the above, the finding of a year round stimulation of phytoplankton primary productivity in this study agrees in part with results of other studies which found photosynthesis stimulation at times of low ambient water temperatures. Most studies however, have found productivity inhibition during high summer ambient temperatures, a phenomenon not observed here. Although most other studies were done at lower latitudes and involved higher average ambient water temperatures than are found at Lake Wabamun, inhibition of productivity has been found (Gurtz and Weiss, 1972; Warinner and Brehmer, 1966) at temperatures within the summer temperature range of Wabamun. The reason for this discrepancy is not known.

7. Overall effects

Wheelock (1969) pointed out that as well as competing with phytoplankton for nutrients in the effluent areas, the large stands of aquatic macrophytes are competing with phytoplankton for light. It is hard to estimate what effect this competition for light has in counteracting the temperature stimulation of phytoplankton productivity. Most of the productivity increment occurs close to the surface of the water column where shading by macrophytes would be least pronounced.

Although no data on the subject were gathered, it seems reasonable that plankton respiration would be stimulated by increased temperatures in effluent areas. Respiration apparently is often stimulated at least as much as photosynthesis and perhaps more (Tilly, 1972; Kevern and Ball, 1965). This further complicates interpretation of results obtained here since such increased respiration (if it is occurring) may counteract productivity increases in the heated areas both by reducing the net 24 hour productivity of phytoplankton and by increasing the respiration of zooplankton. It is thus not known what effects temperature may be having on overall community metabolism, although others (Lee and Veith, 1971; Levin _et al_., 1971; Pidgaiko _et al_., 1972) suggest that it will be speeded up as will nutrient regeneration. This stands to reason, and it seems logical that the plankton community may be functioning at an overall higher rate as a result of increased temperatures with a net increase in growth that may be available to higher trophic levels. Patalas (1970) has presented evidence for this and even for a slight increase in ecological efficiency. Whether this applies to Lake Wabamun is unknown and requires further research.

Another factor to consider at Lake Wabamun is the long period of daily darkness in the winter. Although daytime net productivity continued in the open area through winter, the long diel period of darkness may greatly reduce the 24-hr net amount of phytoplankton production in that period of the year.

Thus, on the basis of this study and considering the complicating factors mentioned above, it can only safely be stated that net daytime productivity of the phytoplankton (as measured with the _in situ_ C^{14} uptake method) was stimulated by the thermal effluent at certain places and depths in the effluent zones.

Having ascertained the general relationship of temperature increases to productivity increases, the extent of ice-free areas, and the general distribution of the thermal plumes, at Lake Wabamun, it was decided to obtain an estimate of the increase in daytime phytoplankton net productivity throughout the year as a result of the operation of the thermal power plants. Such an estimate will be uncertain at best, especially considering the many qualifications mentioned previously with respect to interpretation of results. However, it will at least indicate the order of magnitude of the effect.

A map (from Nuttall, in Gallup, 1971) depicting Kapasiwin Bay surface temperatures and containing temperature depth profiles for August 12, 1970, was used to obtain an estimate of the horizontal and vertical distribution of the thermal plume. From this, the temperature increments involved in specific areas and depths were determined and these increments were used as representative of the thermal plume during the ice-free season. The relationship between temperature increments and productivity increments was taken from Figure 30-a. An average vertical distribution of summer productivity in the main lake was approximated from individual vertical distribution curves including those in Figure 11. Thus, knowing the average temperature increments for the various water strata, the horizontal extent of these strata, and the unaffected productivity of these strata, the overall effect of the thermal effluent on daytime net productivity was calculated for the ice-free season. Productivity results from station WO and KB during the period of winter cover, and the extent of the ice-free regions as shown in Figure 18, allowed a calculation of winter net daytime productivity in the Kapasiwin Bay region.

It was determined that within the affected region of Kapasiwin Bay (as delineated in Figure 18) daytime net phytoplankton productivity was increased by 2% during the period when productivity was continuing in the main lake. Continuous winter production in the open areas added an amount equal to 12% of unaffected production, which, when combined with the summer increase, gave an annual increase of 14% in Kapasiwin Bay. When related to the rest of the lake, this is approximately a 1% increase in the annual phytoplankton production of the whole lake as a result of the operation of the Wabamun power plant. The Sundance power plant now discharges a similar amount of waste heat and so we may estimate that a 2% increase in annual net daytime phytoplankton production of the whole lake results from the operations of both power plants.

Considering the superficial nature of the Wabamun thermal plume and its consequent small volume relative to the total volume of Kapasiwin Bay and of the whole lake, it is understandable that the overall increase in summer productivity is quite small. Also, because of factors such as increased turbidity and macrophyte shading as discussed previously, the summer increase may be further reduced.

Thus, the maintenance of an ice-free zone in winter emerges as the most significant thermal effect with respect to phytoplankton productivity. Light may penetrate an area of the water around the discharges that would otherwise have unmeasurable production during the period of ice and snow cover. Although much of the water volume of the ice-free zones does not show temperatures that are greatly affected by the discharges, photosynthesis continues in these cold waters nonetheless.

It has thus been shown that there is an increase in the daytime phytoplankton net productivity in Lake Wabamun as a result of thermal discharges. In other words, more light energy is being fixed by phytoplankton. A major question remains unanswered, however, and that is to what extent daily (24 hour) net productivity of the phytoplankton is affected. This is the component of productivity that is of most importance to higher trophic levels.

GENERAL DISCUSSION

Stimulation of phytoplankton photosynthesis by thermal effluents in Lake Wabamun can not be considered a harmful effect; consequently, the temperature regimes associated with the present thermal discharges are satisfactory with respect to this aspect of the lake ecosystem. From reports in the literature reviewed earlier, it seems that the present temperature increments should not be exceeded, however, as productivity may be inhibited at temperatures much in excess of 30 °C.

As mentioned earlier, the greatest effect of the thermal effluents on the primary producers (epiphytes, macrophytes, phytoplankton) in Lake Wabamun is not a direct temperature effect, but results from the absence of winter ice and snow cover (Allen, 1973; Klarer, 1973). Light may penetrate the water all year in the discharge areas, allowing a continuous year round pattern of photosynthesis.

The discharge of waste hot water to lakes, streams, and the ocean, is a common occurrence in the industrialized world. Most cases of thermal pollution have not been proved to be drastically harmful to aquatic biota (Cairns,1956; Coutant, 1970; Levin _et_ _al_., 1971), although this statement is based largely on investigations at temperate latitudes. Thermal discharges in the tropics apparently can be much more harmful because tropical organisms are usually living at temperatures that are already close to their upper lethal limits (Bader et al., 1970).

A ten-fold increase in thermal electric generating capacity between the years 1970 and 2000, has been forecast for western Canada (Bruce, 1973). This will probably mean a parallel increase in heated discharges to aquatic environments. While this could mean increases in harmful effects to these aquatic environments, it does not have to. Coutant (1970) has pointed out that problems associated with thermal effluents are more related to the design of power plants than to the absolute amount of heat discharged. This statement is supported by the situation at Lake Wabamun. Excessive growths of aquatic macrophytes and possible effects of increased temperatures on whitefish spawning and development could be avoided by placing discharge points at deeper areas of the lake. Recirculation effects on plankton, if adverse, could be avoided by a study of lake currents and proper placement of intake and disharge points.

It has already been stated that the most marked effect on aquatic plants by the thermal effluents at Lake Wabamun occur during the winter period of ice cover. This is also the time of the greatest threat to whitefish spawning and development, and a time when evaporation of water from discharge areas may be significant with respect to lake water balance (Nuttall, in Gallup, 1971). All these effects could be avoided by using thermal effluents for some form of heating purposes during winter, and only discharging them to the lake in the summer. Ironically (considering the climate), no economical winter use of the warmed waters has yet been found.

The desirability of including ecological studies in the planning of thermal electric generating stations is well illustrated by the situation at Lake Wabamun. Such studies should be specific to each situation if adverse effects of thermal discharges are to be minimized (Levin et al., 1971; Coutant, 1970). Hopefully, the numerous power developments anticipated for the future will include such studies.

SUMMARY OF RESULTS

A. Main Body of the Lake

1. Lake Wabamun summer surface water temperatures were about 20 °C, and the maximum recorded was 23.5 °C. Summer temperature stratification was rare and transient. Ice cover was from November to April inclusive, with up to 1 meter of combined ice and snow cover occurring.
2. Turbidity was low in winter and June, high in April-May and July-September. 1% light penetration was found at about 6-7.5 meters in the water column during July-August. Snow cover, versus only ice cover, strongly reduced light penetration (min. 0.05% of incident) into the water column.
3. Wabamun is a hardwater, bicarbonate lake with orthophosphate levels typical of a moderately eutrophic lake. Silicate was the only dissolved solid showing obvious seasonal fluctuations.
4. Cell numbers for five phytoplankton groups (blue-greens, greens, diatoms, flagellates, and ultraplankton) throughout a year showed a maximum of about 30,000 total cells/ml in October, 1971. Blue-greens were dominant in July-September, important taxa being Anabaena, Aphanocapsa, Coelosphaerium, and Lyngbya limnetica. Ultraplankton were important in September-November and January-May. Diatoms were important in April-May, briefly in June, and in November-December. Flagellates were

important in winter. Total crop was high in July-October, low in November-March, high in April-May, and low in June. Winter lows (about 1500 cells/ml) were coincident with snow cover on the ice. The spring pulse started when snow had melted off the ice cover and peaked shortly after breakup.

5. Phytoplankton chlorophyll a concentrations corresponded to those of a moderately eutrophic lake, being high in April-May, low in June, high in July-September, moderate in October-December, and low in January-March. The latter low was associated with snow and ice cover. The highest mean concentration was 16.4 mg/m³ in August, the lowest 0.8 mg/m³ in March. Individual highs and lows were 19.1 and 0.8 mg/m³ respectively.
6. Phytoplankton primary productivity was high in July-August, moderate in October-December, undetectable under ice and snow cover in January-March, and moderately high from April to July. Midday productivity (1000-1400 hr.) extended to a depth of 6 m in July-August, and during May-August comprised 35% of daytime production. Maximum midday productivity recorded was 115.8 mgC/m³/hr. Maximum recorded daytime net production was 3,045 mgC/m², and annual daytime phytoplankton net production was 170 gC/m². July-August daytime production averaged about 1500 mgC/m². Considering phytoplankton productivity, Lake Wabamun ranks as moderately eutrophic.
7. Assimilation ratio optima averaged about 6.5 in July-

August and about 3.0 in May-July, 1972. 8.6 was the highest optimum recorded.

8. Phytoplankton cell numbers, chlorophyll a, productivity, and turbidity showed a general positive correspondence. Low phytoplankton parameters and assimilation ratios in June indicated nutrient deficiency. Horkan (1971) found highest zooplankton numbers at that season. This may indicate zooplankton grazing effects on the phytoplankton. The effect of snow cover in limiting light penetration apparently was responsible for winter lows in phytoplankton parameters.

B. Thermal Effects

9. The heated effluent formed a surface plume radiating from discharge canals. Temperature increments approximated 8 C° in summer and 15 C° in winter.
10. Turbidity (using Secchi disc) was consistently higher in the effluent areas, consequently it was assumed that light penetration was inhibited. Ice-free regions surrounding discharge canals allowed significant light penetration of the water column in winter.
11. No changes in dissolved solids were evident in the thermal effluents.
12. There were no apparent differences in species composition of the phytoplankton between heated and unheated areas. Surface total cell numbers at station WO were lower than at station 19 in mid-August to mid-

November, but higher in December and early March at the surface and 1.0 meter depths. Total cell numbers did not differ noticeably between heated and unheated areas at any other time or depth. Thermal effects on plankton may depend on recirculation of plankton through the power plants.

13. Comparisons of phytoplankton chlorophyll a concentrations in heated and unheated areas corresponded to the cell number comparisons above.

14. In the summer of 1970, prior to the operation of the Sundance power plant, productivities at station SO were similar to those of other Sundance area stations, but somewhat lower than surface productivities of the main lake.

15. In 1971-72, effluent station productivities were consistently higher at the surface of the water, slightly higher at 0.5 m depth, and at 1 m, generally no greater than productivities in the main lake.

    Surface productivities were consistently higher at nearshore stations than in the main lake, possibly because of algal adaptation to higher mean light levels near shore. Effluent stations had greater productivity than unheated nearshore stations at the surface, generally greater productivity at 0.5 m, and sometimes greater productivity at 1 m.

16. Comparisons of intake and effluent station productivities indicated that phytoplankton

photosynthesis was stimulated by passage through the power plants and the accompanying temperature rise.

17. Temperature, productivity, and assimilation ratio showed greatest increases in the effluents near the water surface and in winter. Increases in assimilation ratios showed that photosynthesis was stimulated. Increases in productivity were positively correlated with increases in temperature, the Q_{10} for all productivity values being 2.6, for surface comparisons being 3.8, and for subsurface comparisons being 1.6.

    Stimulation of photosynthesis may be a direct temperature effect and/or a result of increased nutrient availability in the heated areas.

    Lower Q_{10} values for subsurface comparisons, and the ordinate intercept of regression lines indicated production in effluent areas was lower than in other areas of similar temperatures. Higher turbidity in heated areas may have been responsible.

18. Several other studies have reported thermal effluent stimulation of phytoplankton productivity at times of low ambient temperatures but rarely a year round stimulation.

19. Macrophyte stands may have reduced phytoplankton productivity in the effluents but probably did not negate the thermal stimulation of productivity because the latter was largely confined to the surface.

    Thermal effects on overall plankton metabolism are unknown and require investigation. It can only be concluded that phytoplankton daytime net primary production was stimulated.

There was an increase in daytime phytoplankton net production in the Kapasiwin Bay region of 2% in summer plus 12% in winter for 14% annually. This represented a 2% annual increase for the whole lake as a result of operations of both power plants. The greatest effect of the thermal effluents on phytoplankton productivity resulted from the maintenance of year round ice-free zones.

20. Increased phytoplankton daytime net productivity is not a harmful effect, consequently, the present thermal regimes are satisfactory regarding this limnological parameter.

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APPENDICES

APPENDIX I

Values for production, chlorophyll a, Secchi disc visibility, temperature, and oxygen concentration at stated times and locations. 1970 production results are for gross production with the oxygen method. 1971-72 production results are for net production with the C^{14} method.

Date	Stn	Z (m)	Production mgC/m³/hr	Chlorophyll mg/m³	Secchi (m)	Temp °C	O2 mg/l
28/5/70	SO	0	23.38			14.3	11.03
		0.5	16.38			14.0	10.39
		1.0	12.48			14.0	11.0
		1.5				14.0	10.8
	5	0	6.23			13.3	10.4
		0.5	11.67			13.3	9.84
		1.5	20.21			12.8	9.16
		2.0	21.04			12.8	9.68
2/6/70	SO	0				16.0	9.87
		0.5	4.41			15.3	10.19
		1.0	20.36			14.3	9.85
		1.5	23.57			14.2	10.8
		2.0	37.02			14.2	9.74
	3	0	16.07		2.67	15.5	9.37
		0.5	16.43			15.0	9.27
		1.5	17.38			13.8	9.42
		2.5	27.14			13.8	8.97
	SI	0	18.75		2.75	14.8	9.42
		0.5	9.79			14.3	9.2
		1.5	15.94			13.8	9.43
		2.5	10.94			13.8	9.27
4/6/70	SO	0	9.26			17.0	11.98
		0.5	5.27			17.0	11.68
		1.0	4.02			17.0	11.68
		1.5				17.0	11.65
11/6/70	SO	0	0.82		1.63	16.3	7.23
		0.5	9.35			16.3	7.27
		1.0	8.26			16.3	7.53
		1.5	14.67			16.3	7.51
		2.0	6.1			16.3	7.69
17/6/70	5	0	7.84		2.12	15.8	9.42
		0.5	11.37			15.5	9.78
		1.5	22.75			14.0	8.2
		2.0	8.04			14.0	8.22
	3	0	7.32		2.53	17.3	8.45
		0.5	4.82			16.8	8.5
		1.5	9.72			15.6	8.44
		2.5	19.07			15.5	8.74

Date	Stn	Z (m)	Production mgC/m^3/hr	Chlorophyll mg/m^3	Secchi (m)	Temp °C	O2 mg/l
23/6/70	5	0	8.82		1.90	18.0	8.6
		0.5	17.93			17.8	8.58
		1.5	12.61			16.8	7.98
		2.0	31.43			16.6	7.97
	SI	0	1.2		1.57	18.8	8.96
		0.5	15.6			18.8	8.24
		1.5	19.19			17.8	8.44
		2.5	17.67			17.0	8.45
30/6/70	3	0	31.95			13.5	8.78
		0.5	1.25			13.5	8.43
		1.5	13.19			13.5	8.42
		2.5	2.16			13.5	8.43
	SO	0	5.35			13.0	7.61
		0.5	16.03			13.0	7.83
		1.0	17.58			13.0	7.81
		1.5	14.52			13.0	7.55
2/7/70	SI	0	3.59		1.88		7.59
		0.5	31.75				7.63
		1.5	33.59				7.53
		2.5	26.33				7.58
	5	0	7.48				7.87
		0.5	31.83				8.04
		1.5	12.5				8.01
		2.0	31.17				8.43
	SO	0	11.97		1.73		8.16
		0.5	26.0				7.78
		1.0	35.04				8.01
		1.5	17.92				8.08
		2.0	16.08				8.19
8/7/70	5	0	38.24		1.55	21.8	7.31
		0.5	39.26			21.4	7.6
		1.0	28.89			20.5	7.88
		1.5	14.81			20.3	8.04
	SO	0	25.55			23.0	7.9
		0.5	28.91			22.8	7.8
		1.0	36.55			22.1	7.75
		1.5	9.41			22.0	7.93
	3	0	27.37		1.74	22.3	8.52
		0.5	31.49			21.8	8.51
		1.5	27.02			20.9	8.51
		2.5	12.11			20.4	8.09
15/7/70	SI	0	2.97		1.92	22.6	9.42
		0.5	11.91			22.2	9.6
		1.5	20.09			21.6	8.78
		2.5	16.82			21.1	8.57

Date	Stn	Z (m)	Production mgC/m^3/hr	Chlorophyll mg/m^3	Secchi (m)	Temp °C	O2 mg/l
	6	0	14.72		2.14	22.2	8.59
		3.0	8.59			20.5	8.48
		6.0	-2.08			20.1	8.19
		9.0	-13.4			17.9	3.5
	SO	0	7.19		1.96	23.5	9.93
		0.5	10.34			23.4	11.07
		1.0	7.85			22.5	10.52
		1.5	35.69			21.5	8.58
		2.0	14.74			21.5	8.54
30/7/70	SO	0	17.65		1.51	18.0	7.54
		0.5	22.65				7.52
		1.0	30.59				7.6
		1.5	27.94				7.65
		2.0	30.0				7.63
	SI	0	13.81		1.52	17.5	7.57
		0.5	42.95			17.5	7.62
		1.5	36.51			17.5	7.59
		2.5	30.37			17.3	7.63
	6	0	28.6		1.65	18.3	6.86
		3.0	19.7			18.1	6.87
		6.0	-6.99			18.0	6.86
		9.0	-2.22			18.0	6.8
5/8/70	SO	0	10.05			24.0	9.63
		0.5	2.99				9.55
		1.0	3.8				7.61
		1.5	11.41			19.8	7.61
	3	0	17.28		2.50		7.7
		0.5	14.77				7.61
		1.5	28.16				7.60
		2.5	35.23				6.77
	5	0	17.34				7.4
		0.5	17.63				7.71
		1.0	23.41				7.59
		1.5	28.91				7.50
13/8/70	SO	0	0.30		1.82	20.5	7.15
		0.5	19.95			20.5	7.10
		1.0	10.13			20.5	7.03
		1.5	25.79			20.5	6.99
		2.0	24.25			20.5	7.01
	19	0	14.18			18.8	7.74
		1.0	40.02			18.8	7.82
		2.0	20.17			18.8	7.83
		3.0	13.23			18.8	7.81
	WO	0	3.79		1.85	25.6	7.21
		0.5	11.39			24.2	7.49
		1.5	26.28			20.7	7.59

Date	Stn	Z (m)	Production mgC/m^3/hr	Chlorophyll mg/m^3	Secchi (m)	Temp $^\circ$C	O2 mg/l
		2.5	8.76			20.6	7.56
19/8/70	6	0	28.12		2.00	18.9	8.45
		3.0	29.94			17.3	8.34
		5.0	6.57			17.1	8.38
		6.0	5.48			17.0	8.42
	WO	0	29.02		1.60	26.9	8.00
		0.5	42.69			21.2	7.52
		1.5	36.54			18.8	6.77
		2.5	25.94			17.3	6.71
	8	0	2.09		2.04	16.5	8.08
		0.5	14.61			16.5	8.07
		1.0	17.75			16.4	8.06
		1.5	13.92			15.5	8.42
		2.0	21.57			15.0	8.75
26/8/70	WO	0	12.9		1.55	23.7	7.21
		0.5	14.12			21.8	7.25
		1.5	23.95			16.3	7.66
		2.5	17.81			16.0	7.61
	19	0	18.89		1.67	18.3	7.71
		1.0	16.73			18.3	7.8
		2.0	12.7			18.3	7.84
		3.0	13.94			18.3	8.00
	SO	0	11.03		1.75	18.5	7.41
		0.5	24.58			18.5	7.47
		1.0	22.69			18.5	7.34
		1.5	17.65			18.5	7.40
		2.0	11.35			18.5	7.24
19/9/70	WO	0	32.35		2.13	21.5	9.5
		0.5	34.11			18.8	9.46
		1.5	22.15			15.5	9.24
		2.5	54.51			14.8	6.73
	19	0	0.37		2.00	13.3	11.02
		1.0	20.02			13.0	11.44
		2.0	21.50			12.0	11.0
		3.0	15.57			11.6	11.01
	8	0	6.09			13.3	11.19
		0.5	13.71			13.3	11.16
		1.0				12.8	1.04
		1.5	8.76			11.8	11.08
		2.0	12.95			11.6	12.54
5/10/70	WO	0	17.53			18.5	9.60
		1.0	9.53			12.3	9.90
		2.0	8.38			12.0	10.09
2/11/70	SO	0	0.54			2.5	13.21

Date	Stn	Z (m)	Production mgC/m³/hr	Chlorophyll mg/m³	Secchi (m)	Temp °C	O2 mg/l
		0.5	7.06			3.0	13.0
		1.0	3.80			3.0	13.0
20/5/71	6	0.5		6.41	2.50	12.3	
		2.0		8.06		12.0	
		4.0		8.59		11.5	
		6.0		6.94		11.0	
	SI	0.5		5.03	2.00	12.5	
		2.0		2.15		12.0	
	SO	0.5		4.28	1.75	14.5	
		1.5		3.68		12.5	
	19	0.5		3.16	2.00	12.0	
		2.0		3.67		11.5	
10/6/71	WO	0.5		4.21	2.00	17.5	
		1.5		5.92		15.2	
	SO	0.5		3.17	1.00	18.8	
		1.5		1.75		15.7	
	6	0.5		2.13	3.00	16.1	
		2.0		2.75		14.8	
		3.5		2.39		14.7	
		5.0		5.92		14.5	
		6.5		4.09		14.3	
		8.0		4.8		14.2	
28/6/71	WO	0	23.68		1.40	20.0	
		0.5	34.87			17.0	
		1.0	43.04			15.5	
		2.0	23.34			14.5	
	19	0.5	15.33		1.60	15.0	
		1.5	20.73			15.5	
		2.5	35.65			15.5	
		3.5	14.79			15.0	
5/7/71	SO	0	18.62	5.38	0.60	19.4	
		0.5	7.16	7.79		19.6	
		1.0	2.68	6.44		19.6	
		1.5		6.56		19.4	
	19	0		7.56		14.5	
		0.5				14.7	
		1.0		5.0		14.7	
		1.5		6.94		14.5	
		2.5		6.3		14.5	
		3.5		5.0		14.4	
		4.5		12.4		14.3	
		5.5		6.69		14.1	
8/7/71	19	0	10.38	7.68	1.75	15.5	
		1.0	28.22	7.71		15.5	

Date	Stn	Z (m)	Production mgC/m^3/hr	Chlorophyll mg/m^3	Secchi (m)	Temp °C	O2 mg/l
		2.0	33.65	8.38		15.0	
		3.0		16.33		14.7	
	20	0	10.31		1.75	15.5	
		1.0	27.95	9.78		15.5	
		2.0	30.53	8.95		15.0	
		3.0		9.37		15.0	
	21	0	10.55	7.58	1.75	14.5	
		1.0	32.87	9.11		14.5	
		2.0	40.33	10.0		14.5	
		3.0		13.21		14.5	
12/7/71	WO	0	14.18	12.25	1.40	17.0	
		0.5	38.26	12.73		17.0	
		1.0	51.46	11.67		17.0	
		2.0	39.42	14.85		16.0	
	19	0	8.14	14.07	1.50	14.0	
		0.5	61.12	11.53		14.0	
		1.0	70.59	13.71		14.0	
		2.0	58.95	14.2		14.0	
15/7/71	WO1	0	18.18	6.86		24.7	
	WO2	0	18.18	7.21		24.9	
	WO3	0	18.76	7.53		25.3	
	WO4	0	2.82	6.86		25.2	
	19	0	17.27	11.67		21.7	
19/7/71	SO	0	52.41	10.8	1.45	25.8	
		0.5	78.56	12.4		23.0	
		1.0	57.8	10.9		19.3	
	19	0	20.39	19.3	1.75	22.8	
		0.5	34.67	7.82		22.7	
		1.0	35.96	8.12		22.1	
		2.0	40.81	10.5		19.0	
21/7/71	19	0	29.44	8.90	1.85	21.7	
		0.5	35.96	19.9		21.5	
		1.0	32.19	8.60		21.4	
		1.5		8.41		21.3	
		2.0		8.55		21.3	
		2.5		10.3		21.1	
		3.0	17.06	10.0		20.6	
		3.5	12.08	9.05		19.5	
		4.0	15.84	10.6		18.2	
		5.0		10.6		17.0	
		6.0		9.27		16.6	
		7.0		10.4		16.0	
28/7/71	WO	0	21.84	8.7		23.7	
		0.5	35.96	6.6		23.0	

Date	Stn	Z (m)	Production mgC/m³/hr	Chlorophyll mg/m³	Secchi (m)	Temp °C	O2 mg/l
		1.0	28.09	9.58		22.5	
	19	0	21.34	10.2	1.75	20.0	
		0.5	38.97	11.1		20.0	
		1.0	48.37	11.67		20.0	
		2.0	69.67	13.7		19.5	
3/8/71	WO	0	34.80	6.2		27.5	
		0.5	36.63	8.0		27.2	
		1.0		8.0		24.0	
		2.0		6.9		19.7	
	19	0	19.71	8.1	2.10	21.2	
		0.5	37.18	7.6		21.2	
		1.0	44.20	8.0		20.6	
		2.0	44.91	12.0		20.3	
5/8/71	WO1	0	32.60	7.5	1.65	30.0	
	WO2	0	27.34	5.7		26.9	
	WO3	0	38.63	12.0		23.0	
	WO4	0	28.53	6.5		28.0	
9/8/71	SO	0	54.82		1.40	22.8	
		0.5	81.58	8.6		22.7	
		1.0	78.63	10.0		22.6	
		2.0		5.0		22.5	
	19	0	31.85			22.0	
		0.5	64.82	11.8	1.50	22.0	
		1.0	67.81			22.0	
		2.0	64.99			21.9	
12/8/71	19	0	18.15	8.0	1.90	22.5	
		0.5	50.71	7.5		22.5	
		1.0	52.98	7.0		22.5	
		1.5	49.46	8.5		22.5	
		2.0	37.52	7.5		22.5	
		2.5	32.39	8.5		22.5	
		3.0	21.06	8.5		22.5	
		3.5	13.40	8.0		22.5	
		4.0	8.21	8.0		22.5	
		5.0	5.90	8.5		22.5	
		6.0	1.73	8.5		22.5	
		7.0		7.5		22.5	
16/8/71	SO	0	45.59	8.1	1.55	19.6	
		0.5	31.82	8.0		19.6	
		1.0	19.88	7.9		19.6	
		2.0		8.8		19.6	
	19	0	36.43	10.2	1.50	19.6	
		0.5	49.15	9.5		19.6	
		1.0	37.38	9.8		19.6	

Date	Stn	Z	Production	Chlorophyll	Secchi	Temp	O2
		(m)	mgC/m^3/hr	mg/m^3	(m)	°C	mg/l
		2.0	15.33	10.7		19.6	
18/8/71	19	0	73.03	17.5	1.60	18.1	
		0.5	90.16	15.5		18.1	
1035-1440 hr.		1.5	66.18	16.5		18.1	
		3.0	18.89	19.0		18.1	
		4.5	4.17	14.5		18.1	
		6.0	1.87	15.5		18.1	
		0	65.74	16.0	1.61	18.7	
		0.5	115.50	18.0		18.7	
1440-1840 hr.		1.5	66.38	17.5		18.7	
		3.0	11.80	16.5		18.7	
		4.5	2.41	19.0		18.7	
		6.0	1.08	14.5		18.7	
		0	6.24	19.0	1.50	19.1	
		0.5	11.17	16.5		19.1	
1840-2240 hr.		1.5	3.29	17.5		19.1	
		3.0	0.47	13.5		19.1	
		4.5	1.02	17.0		19.1	
		6.0	1.63	17.5		19.1	
		0	0.95	13.0		18.9	
		0.5	0.58	15.0		19.0	
2240-0240 hr.		1.5	-0.07	16.0		19.0	
		3.0	-0.37			19.0	
19/8/71		4.5	1.05	15.0		19.0	
		6.0	0.0	14.5		19.0	
		0	12.14	19.5		18.7	
		0.5	7.36	8.1		18.8	
0240-0640 hr.		1.5	1.42	17.2		18.9	
		3.0	0.3	13.5		19.0	
		4.5	0.61	11.5		19.0	
		6.0	0.24	13.5		19.0	
		0	105.5	26.0	1.80	18.9	
		0.5	111.8	17.0		18.9	
0640-1040 hr.		1.5	74.69	16.5		18.9	
		3.0	15.94	16.5		18.9	
		4.5	1.87	16.5		18.9	
		6.0	4.21	17.0		18.9	
		0	43.89			20.5	
		0.5	69.2	12.5		20.1	
1040-1440 hr.		1.5	114.14	18.5		19.6	
		3.0	39.79	16.5		19.2	
		4.5	8.72	18.0		19.0	
		6.0	2.37	17.0		19.0	
25/8/71	WO	0		3.85	1.50	25.0	
		0.5		3.5		25.0	
		1.0		1.65		21.1	
		2.0		11.65		20.5	

Date	Stn	Z (m)	Production mgC/m³/hr	Chlorophyll mg/m³	Secchi (m)	Temp °C	O2 mg/l
	19	0	26.63	12.4	1.60	19.2	
		0.5	68.08	11.4		19.2	
		1.0	106.27	12.4		19.2	
		2.0	83.07	12.0		19.2	
8/9/71	SO	0	43.82	9.7	1.55	23.6	
		0.5	64.01	10.9		23.2	
		1.0	34.9	10.6		20.8	
	19	0	23.68	9.2	1.55	16.5	
		0.5	35.21	10.6		16.5	
		1.0		6.3		16.5	
		2.0	33.72	10.0		16.5	
25/9/71	WO	0	42.40	7.5	1.70	16.4	
		0.5	28.9	7.3		16.0	
		1.0	16.15	8.6		13.6	
		2.0				11.1	
	19	0	47.18	9.3		9.0	
		0.5	45.93	9.55		9.0	
		1.0	31.24	9.1		9.0	
		2.0	13.33	8.65		8.8	
9/10/71	SO	0	32.19	5.75	1.75	18.5	
		0.5	52.64	6.3		17.4	
		1.0	45.83	5.55		13.0	
	19	0	13.30	7.35	2.10	10.2	
		0.5	33.89	7.0		10.1	
		1.0	38.06			9.8	
		2.0	38.53	5.9		9.8	
23/10/71	WO	0	37.62	5.8	2.40	15.1	
		0.5	30.	5.75		12.0	
		1.0	32.26	7.0		8.0	
		2.0	23.78	6.35		6.8	
	19	0	7.36	6.0	2.40	6.5	
		0.5	19.47	6.2		6.3	
		1.0	22.83	6.4		6.3	
		2.0	24.63	6.95		6.0	
16/11/71	WO	0	27.78	6.71	2.30	14.5	
		0.5	16.24	6.39		6.8	
		1.0	19.89	6.61		4.8	
		2.0	18.36	6.9		4.2	
30/11/71	SC	0	14.01	2.45		1.1	
		0.5	17.60	6.48		1.1	
		1.5	18.35	8.18		1.6	
		3.0	7.77	7.45		2.0	
		4.5	4.14	5.6		2.9	

Date	Stn	Z (m)	Production mgC/m³/hr	Chlorophyll mg/m³	Secchi (m)	Temp °C	O2 mg/l
		6.0	1.83	4.95		3.5	
11/12/71	WO	0	18.22	6.73	2.80	10.0	
		0.5	25.69	6.73		9.0	
		1.0	22.37	6.7		6.0	
		2.0	20.94	6.7		4.0	
6/1/72	WO	0	3.09	6.3	1.60	2.2	
		0.5	17.71	6.13		2.2	
		1.0	15.37	6.93		2.1	
		2.0	12.45	6.46		2.1	
7/1/72	6	0		1.91	3.50	0.9	14.3
		3.0		1.6		2.3	11.5
		6.0		0.83		4.0	5.3
		8.5				4.2	2.1
8/1/72	SC	0	-0.17	2.23	4.50	0.2	12.8
		0.5	-1.76	1.78		0.7	12.8
		1.5	0.0	1.94		1.4	12.4
		3.0	0.68	1.45		2.7	11.3
		4.5	-1.29	1.26		3.3	10.1
		6.0	-1.02	1.32		3.6	6.8
30/1/72	KB	0	2.65	1.82	2.75	2.7	
		0.5	5.09	1.6		2.3	
		1.0	7.02	1.67		2.3	
		2.0	6.04	1.67		2.3	
2/2/72	WO	0	14.93	1.42		17.8	
		0.5	10.46	1.68		11.5	
		1.0	10.07	1.68		6.5	
	KB	0	2.90	1.64		2.5	
		0.5	10.53	1.68		2.5	
		1.0	7.98	1.24		2.8	
20/2/72	SC	0	-0.75	1.07		0.0	8.7
		0.5	1.64	1.36		1.0	
		1.5	0.56	0.83		2.2	9.1
		3.0	0.09	0.86		3.0	9.4
		4.5	-1.42	1.18		3.3	8.0
12/3/72	WO	0	14.43	1.91		15.0	
		0.5	16.2	2.3		15.0	
		1.0	10.98	2.41		11.2	
	KB	0	2.41	1.99	3.55	7.0	
		0.5	6.65	1.80		6.6	
		1.0	8.11	2.10		6.3	

Date	Stn	Z (m)	Production mgC/m^3/hr	Chlorophyll mg/m^3	Secchi (m)	Temp °C	O2 mg/l
15/3/72	AB	0	-1.12	1.05		0.8	12.5
		0.5	-1.10	0.89		1.0	12.8
		1.5	0.08	1.08		2.3	12.5
		3.0	-2.84	0.92		3.6	10.0
		4.5	0.3	1.15		3.8	9.7
31/3/72	WO	0	40.57	6.83	1.80	16.6	
		0.5	35.12	7.28		15.1	
		1.0	29.66	7.28		8.4	
	KB	0	7.79	6.06	2.40	6.7	
		0.5	29.66	6.01		6.6	
		1.0	32.15	6.72		6.6	
9/4/72	KB	0	16.63	6.90	2.10	3.6	
		0.5	37.60	5.95		3.6	
		1.5	38.56	6.27		3.6	
		2.5	36.11	7.13		3.6	
		3.5	30.22	6.49		3.5	
		4.5	22.32	6.13		3.5	
10/4/72	AB	0	24.39	6.73	2.35	0.5	12.0
		0.5	44.22	10.3		1.5	11.8
		1.5	30.91	10.3		2.8	11.0
		3.0	14.32	7.13		3.0	10.4
		4.5	5.01	7.39		3.0	10.0
19/4/72	WO	0	23.81	9.78	1.70	15.5	
		0.5	33.52	8.05		11.06	
		1.0	16.78	8.91		8.1	
	KB	0	10.35	9.57	1.85	10.0	
		0.5	19.84	8.25		9.7	
		1.0	21.07	8.61		9.3	
28/4/72	WO	0	29.13	11.06	1.25	21.1	
		0.5	46.96	9.21		21.1	
		1.0	35.99	6.73		20.0	
	KB	0	2.96	8.57	1.80	11.0	
		0.5	18.06	8.05		10.9	
		1.0	20.84	8.53		10.8	
2/5/72	SO	0	5.83	9.55		15.7	
		0.5	12.07	8.91		12.1	
		1.0	14.13	9.75		7.4	
	3	0	2.73	9.74	2.00	8.4	
		0.5	13.0	9.74		8.2	
		1.0	11.38	10.6		8.2	
8/5/72	WO	0	14.69	6.38	1.50	20.3	
		0.5	26.41	7.0		20.0	

Date	Stn	Z (m)	Production mgC/m^3/hr	Chlorophyll mg/m^3	Secchi (m)	Temp °C	O2 mg/l
		1.0	24.46	6.74		17.1	
	WP	0	4.82	4.21		11.5	
		0.5	9.14	4.94		11.5	
		1.0	13.98	6.07		11.5	
11/5/72	19	0	0.99	5.74	1.85	13.3	
		0.5	6.64	5.23		11.7	
		1.5	6.96	6.18		10.5	
		3.0	7.35	7.08		9.4	
		4.5	5.81	8.35		8.6	
		6.0	5.52	10.5		8.0	
17/5/72	SO	0	9.91	3.94	1.80	19.7	
		0.5	10.71	4.48		18.0	
		1.0	8.0	3.87		14.2	
	19	0	5.11	3.76	2.40	13.3	
		0.5	6.5	3.6		13.3	
		1.0	7.37	3.6		13.3	
18/5/72	WO	0	17.21	3.34		22.4	
		1.0	20.02	5.70		15.6	
	KB	0	13.45	4.88	2.00	16.2	
		1.0	16.54	2.75		16.2	
	WP	0	10.51	3.4		16.6	
		1.0	12.55			16.6	
25/5/72	WO	0	14.82	6.63	1.90	21.0	
		0.5	10.31	4.08		19.0	
0430-0830 hr.		1.0	7.63	2.83		15.9	
	KB	0	8.96	4.15	2.00	16.7	
		0.5	8.89	4.4		16.6	
		1.0	8.11	3.31		16.6	
	WO	0	12.96	4.17	1.65	21.1	
		0.5	11.33	3.6		18.2	
0830-1230 hr.		1.0	11.23	4.75		14.6	
	KB	0	6.89	3.18	1.80	15.6	
		0.5	12.62	3.36		15.6	
		1.0	10.68	3.47		15.5	
	WO	0	12.18	3.83	1.65	20.5	
		0.5	12.42	4.97		16.2	
1230-1630 hr.		1.0	10.09	5.0		13.0	
	KB	0	12.83	3.83	2.10	15.0	
		0.5	14.02	4.10		15.0	
		1.0	16.1	3.33		15.0	
	WO	0	14.82	3.65	1.85	21.0	
		0.5	10.31	4.8		15.7	
1630-2030 hr.		1.0	9.08	4.42		14.1	
	KB	0	9.75	3.58	1.80	15.5	
		0.5	9.98	3.44		14.8	

Date	Stn	Z (m)	Production mgC/m³/hr	Chlorophyll mg/m³	Secchi (m)	Temp °C	O2 mg/l
		1.0	8.95	4.2		14.7	
30/5/72	SO	0	13.37	8.0	2.00	22.1	
		0.5	12.51	3.96		17.3	
		1.0	11.21	2.87		15.4	
	19	0	4.84	3.83	2.90	17.2	
		0.5	8.77	3.86		15.3	
		1.0	10.60	3.43		15.0	
5/6/72	WO	0	4.60			27.0	
		0.5	7.74	1.24		23.9	
		1.0	7.87			19.9	
	19	0	3.3		3.50	19.3	
		0.5	6.05	1.7		19.0	
		1.0	7.86			18.5	
7/6/72	SO	0	7.34	1.26		25.0	
		1.0	10.35	2.55		20.1	
	3	0	10.95	3.57		20.5	
		1.0	14.64	2.58		20.0	
	1A	0	8.36	1.92		22.2	
		1.0	14.17	1.64		22.1	
8/6/72	MB	0	16.72	2.92		19.9	
		0.5	16.72	2.67		20.0	
		1.0	17.50	3.0		20.0	
		1.5	11.3	2.75		20.0	
	KB	0.5	15.98	2.8	2.70	18.2	
		1.0	28.93	1.88		18.1	
13/6/72	WO	0	23.53	6.96		21.3	
		0.5	23.14	3.21		21.0	
		1.0	24.47	6.42		16.6	
	WI	0	16.91	3.19		15.3	
		0.5	24.5	3.21		15.3	
		1.0	22.24	7.17		15.3	
15/6/72	SO	0	4.99	2.97		16.8	
	19	0	3.33	3.03		15.9	
	SI	0	5.48	6.80		16.5	
	1A	0	7.02	3.36		16.0	
21/6/72	WO	0	9.70	5.40		24.0	
		0.5	18.17	5.41		22.5	
		1.0	22.81	5.84		18.8	
	19	0	2.91	7.19	2.50	17.8	
		0.5	17.01	7.28		17.7	
		1.0	21.67	7.52		17.6	
22/6/72	SO	0	5.53	3.70		17.0	

Date	Stn	Z (m)	Production mgC/m³/hr	Chlorophyll mg/m³	Secchi (m)	Temp °C	O2 mg/l
	19	0	6.03	4.05	2.65	16.9	
	SI	0	7.74	4.38	2.75	17.1	
	1A	0	9.01	3.58		18.0	
	8	0	7.36	3.92	2.65	17.0	
27/6/72	WI	0	9.44	7.56	2.60	17.8	
		1.0	24.46	6.88		17.8	
	19	0	5.56	8.88	2.70	17.4	
		1.0	23.89	8.51		17.3	
	SI	0	7.25	6.42	2.45	18.0	
		1.0	16.10	5.55		17.0	
29/6/72	6	0	4.11	7.03	3.40	17.3	
		0.5	16.5	6.19		17.3	
		1.0	16.22	5.5		17.3	
		1.5	17.01	6.19		17.3	
		2.0	14.55	6.19		17.3	
		3.0	11.59	6.19		17.2	
		4.0	9.25	6.19		17.2	
		5.0	5.90	6.19		17.2	
		6.0	2.97	6.19		17.2	
		7.0	1.52	6.88		17.2	
		8.0	0.72	8.71		17.2	
		9.0	0.72	8.94		17.1	
5/7/72	WO	0	7.16	4.07	2.55	24.9	
		1.0	10.53	4.58		19.2	
	WI	0	2.64	1.83	2.30	19.5	
		1.0	12.18	3.67		19.2	
	19	0	2.34	4.58	2.75	19.7	
		1.0	10.09	3.67		18.5	
7/7/72	WO	0	6.05	3.03	2.90	25.4	
		1.0	8.73	4.17		19.4	
	SO	0	5.89	2.21		18.8	
		1.0	12.3	3.69		18.5	
	19	0	4.69	2.47	2.70	18.2	
		1.0	9.54	3.08		18.0	
10/7/72	WO	0	17.92	8.2		20.2	
		1.0	20.52	9.29		19.8	
	WI	0	25.5	12.6		17.0	
		1.0	31.56	13.13		17.0	
	WP	0	15.69	5.78		18.0	
		0	12.56	5.59		17.2	
12/7/72	19	0	16.40	7.20	2.00	16.2	
		0.5	5.36	5.99		16.2	
0415-0815 hr.		1.5	8.04	5.8		16.2	

Date	Stn	Z (m)	Production mgC/m³/hr	Chlorophyll mg/m³	Secchi (m)	Temp °C	O2 mg/l
		3.3	3.39	6.17		16.2	
		4.5	1.63	6.85		16.2	
		6.0	0.25	7.49		16.1	
		0	2.91	6.44		17.6	
		0.5	10.9	4.6		17.0	
0815-1215 hr.		1.5	15.88	4.93		16.8	
		3.0	15.6	4.25		16.8	
		4.5	8.22	5.08		16.6	
		6.0	3.5	5.53		16.5	
		0	6.88	2.64	2.10	19.2	
		0.5	10.68	2.64		18.9	
1215-1615 hr.		1.5	19.81	5.08		17.8	
		3.0	15.24	6.89		17.4	
		4.5	9.87	6.06		17.0	
			2.58	4.38		16.8	
		0	8.21	3.08	2.00	19.4	
		0.5	7.16	3.64		19.4	
1615-2015 hr.		1.5	10.44	5.10		17.8	
		3.0	4.75	8.53		17.4	
		4.5	1.36	6.31		17.0	
		6.0	1.18	9.1		16.6	
19/7/72	WO	0	14.88	9.63	1.75	24.3	
		1.0	25.62	8.85		18.8	
	WI	0	8.22	11.1	1.85	18.0	
		1.0	29.96	15.1		17.9	
	WP	0	6.21	5.97		18.2	
		0	4.18	2.81		18.0	
20/7/72	WO	0	10.68	6.06		27.5	
	WO	0	4.85	7.91		25.0	
	KB	0	3.87	7.16		21.8	
	KB	0	8.89	7.39	2.35	21.0	
	WI	0	4.41	7.39	2.25	18.5	
21/7/72	19	0	2.02	5.23	2.35	17.0	
		1.0	13.65	8.66		17.0	
	21	0	3.22	10.8	2.05	17.1	
		1.0	14.36	8.62		17.0	
	6	0	4.13	5.6		17.6	
		1.0	16.24	9.5		17.5	
2/8/72	SO	0	10.23		1.60	24.6	
	19	0	3.11	5.70	2.30	18.8	
	SI	0	5.35	7.10	2.00	18.7	
	1A	0	7.90	3.05	2.50	20.5	
	8	0	6.70	5.53		19.8	

APPENDIX II

Cell counts (as cells/ml) for the five phytoplankton groups and total counts, at stated times and locations.

Date	Stn	Z (m)	Blue-Greens	Diatom	Greens	Flagellates	Ultraplankton	Total
28/6/71	WO	0	4,873	969	4,327	344	1,734	12,248
		1.0	1,000	453	2,124	219	1,500	5,296
		1.5	12,795	1,999	2,359	188	969	18,310
5/7/71	19	0	4,270	455	1,640	78	352	6,796
		0.5	4,270	1,146	1,158	26	273	6,874
		2.5	5,077	1,600	2,065	172	372	9,285
		5.5	8,801	963	403	117	391	10,676
	SO	0	16,058	562	2,110	94	937	19,763
		1.0	7,468	1,843	609	78	578	10,577
8/7/71	21	3.0	11,186	984	1,765	78	734	14,748
	20	1.0	5,650	677	4,153	13	1,250	11,743
		3.0	7,812	1,328	3,572	91	872	13,670
	19	1.0	7,319	216	2,282	204	661	10,684
		3.0	4,608	260	651	39	651	6,210
12/7/71	19	0	9,561	1,704	3,406	187	547	15,404
		0.5	4,674	715	1,482	65	469	7,408
		1.0	9,133	921	2,063	260	901	13,280
		2.0	14,139	2,096	3,033	65	468	19,802
	WO	0	3,437	676	1,171	143	790	6,223
		0.5	8,608	1,437	1,077	343	1,469	12,998
		1.0	4,244	702	1,431	2,200	976	9,556
		2.0	11,425	1,933	4,355	312	1,191	19,216
19/7/71	SO	0	7,546	188	2,265	203	1,547	11,748
		0.5	22,653	478	1,997	87	1,714	26,928
		1.0	13,270	286	1,562	65	742	15,922
	19	0	27,887	26	1,107	234	729	29,983
		0.5	10,019	39	1,036	215	703	12,010
		1.0	17,981	359	688	390	781	20,200
		2.0	19,185	125	1,219	1,030	1,546	23,106
21/7/71	19	0	9,804	117	976	455	951	12,303
		0.5	7,499	60	391	781	1,113	9,842
		3.0	24,333	353	494	159	1,627	27,236
		6.0	12,299	1,153	2,045	71	1,534	17,100
3/8/71	WO	0	11,655	78	156	359	1,984	14,233
		1.0	19,997	343	515	516	2,250	23,622
12/8/71	19	0	8,734	526	569	539	3,196	13,563
		0.5	16,024	546	1,198	573	4,271	22,601
		3.0	13,904	672	514	515	1,499	17,107

Date	Stn	Z (m)	Blue-Greens	Diatom	Greens	Flagellates	Ultraplankton	Total
		6.0	7,754	270	908	425	1,714	11,078
16/8/71	SO	0	11,826	312	857	422	6,218	19,638
		1.0	14,951	203	1,765	359	8,030	25,309
19/8/71	19	0	14,576	578	1,577	235	1,859	18,826
		0.5	9,616	1,127	2,158	1,267	2,934	17,098
		3.0	21,264	1,007	1,997	1,162	2,899	28,330
		6.0	20,603	2,285	3,769	1,894	2,265	30,816
25/8/71	WO	0	3,605	276	396	324	2,896	7,499
		1.0	8,952	1,798	1,859	1,056	3,999	17,654
8/9/71	SO	0	15,342	531	516	172	4,687	21,247
		1.0	22,043	610	609	297	4,796	28,356
	19	0	19,408	662	1,793	234	4,901	26,998
		1.0	17,361	626	937	98	6,484	25,505
25/9/71	WO	0	2,063	702	673	312	3,468	7,218
		1.0	6,733	984	1,686	593	4,468	14,467
9/10/71	19	0	3,828	262	754	443	27,158	32,496
		0.5	9,374	595	1,092	1,340	5,431	17,830
		1.0	14,404	437	484	187	13,717	29,231
		2.0	6,984	453	1,359	156	13,732	21,138
	SO	0	7,218	656	687	1,391	4,844	14,795
		0.5	8,305	455	923	208	5,221	15,115
		1.0	8,072	850	503	781	3,663	13,870
23/10/71	19	0	4,247	483	2,328	994	12,910	20,963
		0.5	8,795	593	578	610	8,764	19,341
		1.0	2,864	533	755	273	6,536	10,962
		2.0	7,527	567	666	1,108	4,545	14,416
	WO	0	4,427	664	911	821	2,266	9,087
		0.5	5,140	1,031	125	485	5,999	12,780
		1.0	2,357	638	1,037	255	16,546	20,835
		2.0	13,169	1,141	1,359	688	6,371	23,091
16/11/71	KB	0	3,624	1,000	422	796	1,781	7,624
		0.5	4,046	1,390	328	625	3,000	9,389
		1.0	5,872	1,262	494	560	3,333	11,522
		2.0	6,134	903	347	890	2,523	10,797
30/11/71	SC	0.5	2,979	1,520	124	1,125	2,802	8,551
		3.0	5,293	1,560	256	1,052	2,997	11,159
		6.0	3,750	1,705	221	130	1,263	7,069
11/12/71	WO	0	2,406	1,593	375	1,453	4,296	10,124
		1.0	906	1,656	0	1,219	4,718	8,499

6/1/72	KB	0	3,008	1,185	703	169	2,291	7,356
		0.5	2,559	1,531	953	5,119	2,276	12,439
		2.0	7,140	1,250	777	359	3,588	13,112
8/1/72	SC	0	120	73	78	224	630	1,125
		0.5	0	109	31	302	948	1,390
		1.5	625	164	55	320	516	1,679
		4.5	664	273	16	102	570	1,625
		6.0	0	234	0	26	260	521
2/2/72	WO	0	33	338	66	104	1,152	1,692
		0.5	160	985	240	120	3,036	4,543
	KB	0	83	1,062	364	354	2,937	4,801
		1.0	8	1,001	48	232	2,059	3,349
20/2/72	SC	0	0	73	31	427	1,312	1,844
		0.5	0	365	37	469	3,244	4,114
		3.0	0	641	136	64	1,017	1,859
		4.5	78	148	18	529	1,805	2,578
12/3/72	WO	0	0	976	55	297	1,000	2,328
		0.5	414	929	78	94	672	2,187
		1.0	0	1,047	109	335	1,086	2,578
	KB	0	109	938	62	23	1,078	2,211
		0.5	0	1,270	215	108	1,123	2,714
		1.0	1,417	1,528	78	279	1,462	4,765
15/3/72	AB	0	0	70	16	336	477	898
		0.5	0	227	24	266	656	1,171
		3.0	52	768	104	78	4,296	5,299
		4.5	0	816	277	87	4,340	5,520
31/3/72	WO	0	521	4,072	121	885	2,899	8,558
		0.5	656	3,875	672	1,125	4,531	10,858
		1.0	52	3,529	0	1,120	2,799	7,499
	KB	0	293	4,179	351	703	2,871	8,397
		0.5	137	4,511	293	625	3,046	8,612
		1.0	0	4,479	330	868	2,760	8,436
10/4/72	AB	0	69	2,691	278	1,961	1,527	6,527
		0.5	117	4,647	234	3,105	1,660	9,764
		3.0	52	4,140	286	1,068	2,291	7,838
		4.5	0	3,983	137	723	2,011	6,855
19/4/72	WO	0	0	8,312	827	1,422	5,234	15,795
		1.0	137	9,081	801	1,153	5,859	17,029
2/5/72	3	0	2,232	4,709	491	580	11,048	19,060
		0.5	0	5,958	446	736	12,387	19,529
		1.0	0	6,294	446	670	8,147	15,556
	SO	0	573	6,509	755	1,119	11,014	19,971
		0.5	67	7,633	647	871	10,401	19,618
		1.0	1,128	6,735	1,474	625	5,191	15,154

8/5/72	WO	0	260	4,948	1,172	990	11,197	18,565
		0.5	0	5,180	1,119	964	9,609	16,872
		1.0	0	2,910	742	527	7,752	12,069
	WP	0	122	2,326	1,024	1,319	9,391	14,182
		0.5	281	2,500	1,000	1,157	9,217	14,154
		1.0	555	3,506	642	902	9,321	14,929
11/5/72	19	0	69	4,551	1,007	521	10,138	16,283
		0.5	0	4,765	922	1,859	13,186	20,732
		3.0	3,983	1,538	1,270	1,367	13,788	27,946
		6.0	2,173	6,320	683	397	8,777	18,350
17/5/72	19	0	375	4,750	593	1,734	6,389	13,842
		0.5	0	3,654	607	1,142	4,723	10,191
		1.0	117	3,359	573	1,471	3,099	8,619
	SO	0	1,046	3,405	321	1,328	5,843	11,944
		0.5	0	3,484	391	1,796	3,687	10,217
		1.0	312	1,834	156	1,224	3,519	7,043
5/6/72	19	0	646	490	541	489	1,229	3,395
		0.5	112	791	669	681	1,607	3,861
		1.0	359	394	284	423	1,167	2,628
	WO	0	281	865	323	645	1,531	3,645
		0.5	416	166	417	250	927	2,177
		1.0	507	91	1,341	899	1,133	4,023
7/6/72	SO	0	39	794	689	182	3,997	5,702
		0.5	156	819	208	182	2,786	4,153
13/6/72	WI	0	946	2,710	374	1,249	269	5,546
		0.5	8,773	2,235	840	1,381	349	13,580
		1.0	1,362	2,822	491	1,205	279	6,171
	WO	0	1,982	1,758	410	1,513	673	6,335
		0.5	844	1,758	313	879	469	4,257
		1.0	976	2,110	333	635	361	4,413
21/6/72	WO	0	3,658	2,773	962	1,561	508	9,465
		0.5	1,497	3,436	1,601	977	625	8,137
		1.0	0	1,987	1,182	981	446	4,598
	19	0	2,645	3,805	1,248	580	201	8,481
		0.5	879	3,182	2,412	559	225	7,257
		1.0	6,959	12,044	1,364	739	327	21,432
22/6/72	19	0	2,441	2,871	566	1,328	830	8,036
	SI	0	2,800	3,324	561	915	446	8,046
	SO	0	2,769	1,372	1,223	600	443	6,405
	1A	0	1,140	507	587	1,039	750	4,023
	8	0	1,780	1,053	701	688	187	4,413
	16	0	8,290	55	55	2,053	223	10,679
29/6/72	6	0	6,054	1,523	403	52	117	8,150
		0.5	27,972	1,808	869	327	260	31,239
		3.0	5,319	689	438	433	99	7,009
		6.0	5,649	936	650	756	115	8,108

		9.0	9,217	2,344	1,544	361	88	13,553
5/7/72	WI	0	6,827	665	649	328	320	8,788
		1.0	10,669	982	1,116	580	480	13,826
7/7/72	19	0	5,182	407	450	139	512	6,692
		1.0	10,175	1,250	1,001	198	229	12,853
	SO	0	2,911	98	336	395	551	4,292
		1.0	8,020	148	591	364	720	9,842
10/7/72	WI	0	7,134	799	1,058	591	903	10,485
		1.0	11,005	1,198	868	399	642	14,113
	WO	0	15,368	753	1,121	739	1,207	19,188
		1.0	13,557	1,771	1,839	538	1,180	18,886
12/7/72	19	0	15,880	1,417	1,004	491	647	19,439
		0.5	12,897	590	1,721	144	972	16,324
		3.0	9,023	938	2,577	645	996	14,178
		6.0	10,874	531	1,760	236	632	14,036
19/7/72	WI	0	14,593	2,329	3,827	922	1,062	22,731
		1.0	19,600	1,627	2,070	1,119	1,120	25,543
	WO	0	14,801	849	1,785	371	1,269	19,080
		1.0	7,827	1,728	1,095	1,022	1,382	13,054
	WP	0	9,759	469	1,447	715	510	12,901
	WP	0	1,539	40	345	1,055	836	3,812
21/7/72	19	0	10,661	476	759	194	818	12,908
		1.0	12,585	918	720	769	1,401	16,392
	21	0	19,429	447	1,776	156	725	22,530
		1.0	9,529	823	1,073	167	344	11,936
	6	0	12,109	1,508	1,014	101	304	15,037
		1.0	18,267	772	1,318	337	713	21,408
2/8/72	19	0	16,302	641	1,007	578	891	19,419
	SI	0	23,514	3,540	1,536	1,146	2,213	31,949
	SO	0	8,421	640	2,382	890	1,953	14,287
	1A	0	3,577	499	1,641	360	2,734	8,811
	8	0	8,734	967	640	641	2,344	13,326

APPENDIX III

Phytoplankton identified from Lake Wabamun, 1971-72.

* not recorded by Wheelock (1969)

Ultraplankton

Cyanophyta

Anabaena sp.
Aphanocapsa sp.
Aphanothece sp.
Chroococcus sp.
Coelosphaerium naegelianum Unger
Coelosphaerium sp.
Gomphosphaeria sp.
Lyngbya limnetica Lemmermann
Merismopedia spp.
Microcystis sp.
Oscillatoria spp.

Chlorophyta

Ankistrodesmus falcatus (Corda) Ralfs
Ankistrodesmus sp.
Asterococcus sp.
Closteriopsis sp.
Closterium sp.
Coelastrum sp.
Cosmarium sp.
Crucigenia sp.
Dictyosphaerium sp.
Lagerheimia sp.
Mougeotia sp.
Oocystis sp.
Pediastrum boryanum (Turp.) Meneghini
Pediastrum duplex Meyen
Pediastrum sp.
Scenedesmus sp.
Selenastrum sp.
Staurastrum sp.
Tetraedron minimum (A. Braun) Hansgirg
Tetraedron sp.

Bacillariophyceae

Asterionella sp.
Fragilaria sp.
Melosira sp.
Stephanodiscus sp.
Synedra sp.
Tabellaria sp.

Flagellates

Ceratium sp.
**Cryptomonas sp.*
Dinobryon sertularia Ehrenberg
Peridinium sp.
**Rhodomonas sp.*